Introduction to
High Energy Physics

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Fermilab/NIU

General Course Information

- Web Page: http://home.fnal.gov/~pushpa/phys684.htm
- Class Schedule:
  Saturdays 10:30 am - Noon, FW227
  Tuesdays 6:00 PM – 7:30 PM
- Contact Email: pushpa@fnal.gov
- Recommended Books:
  - Particle Physics by Martin & Shaw, 3rd edition
  - Introduction to High Energy Physics by Donald Perkins, 4th Edition
  - Quarks and Leptons, Halzen & Martin

- There are plenty of web resources:
  - PDG: http://pdg.lbl.gov/(very useful)

Course Outline

Basic concepts: Particles & Forces, Antiparticles, Dirac equation, Particle Exchange, Feynman Diagrams.

Basics (contd): Natural Units, Kinematics, Cross Section, Production & Decay rates.

Quarks and Hadrons: Properties, Production and decays

Leptons and the Weak Interactions: Lepton multiplets, Lepton numbers, weak interactions, neutrinos: masses and mixing.

Experimental Particle Physics: Particle Accelerators; Physics of Particle Detection, Detectors, Experiments

Space-time symmetries: Gauge theories

≥25% of the Course

The Quark Model: Isospin Symmetry, Color, Light Hadrons, Heavy flavor Physics

Quantum Chromodynamics: Strong Coupling, Confinement, asymptotic freedom; Hadron production, experimental evidence for QCD, deep inelastic scattering, Parton distribution and structure functions.

Course Outline (contd.)

More on the standard Model: Electroweak Interactions, EW unification, W&Z bosons, Higgs Mechanism, Spontaneous symmetry breaking, tests of electroweak theory.

Beyond the standard model: Grand Unification Theory, Supersymmetry, Technicolor, Extra-dimensions, Strings, etc

Brief Synopsis of Cosmology & Particle Astrophysics (if time permits)

An Overview

Particle Physics

The Quest for Basic Building Blocks

has been ongoing from times immemorial –

- The basic "Elements" of nature
  - Greeks: 4 elements – air, water, fire, earth
  - Indians: 5 elements – air, water, fire, earth, space/ether
- All matter was suspected to be made up of "fundamental" building blocks that would be "uncuttable"

  Greeks → "Atomos" Democritus 470 – 380 B.C.

  Indians → "Anu", "Paramanu" Kanada 600 B.C

  (Indivisible entities of matter)

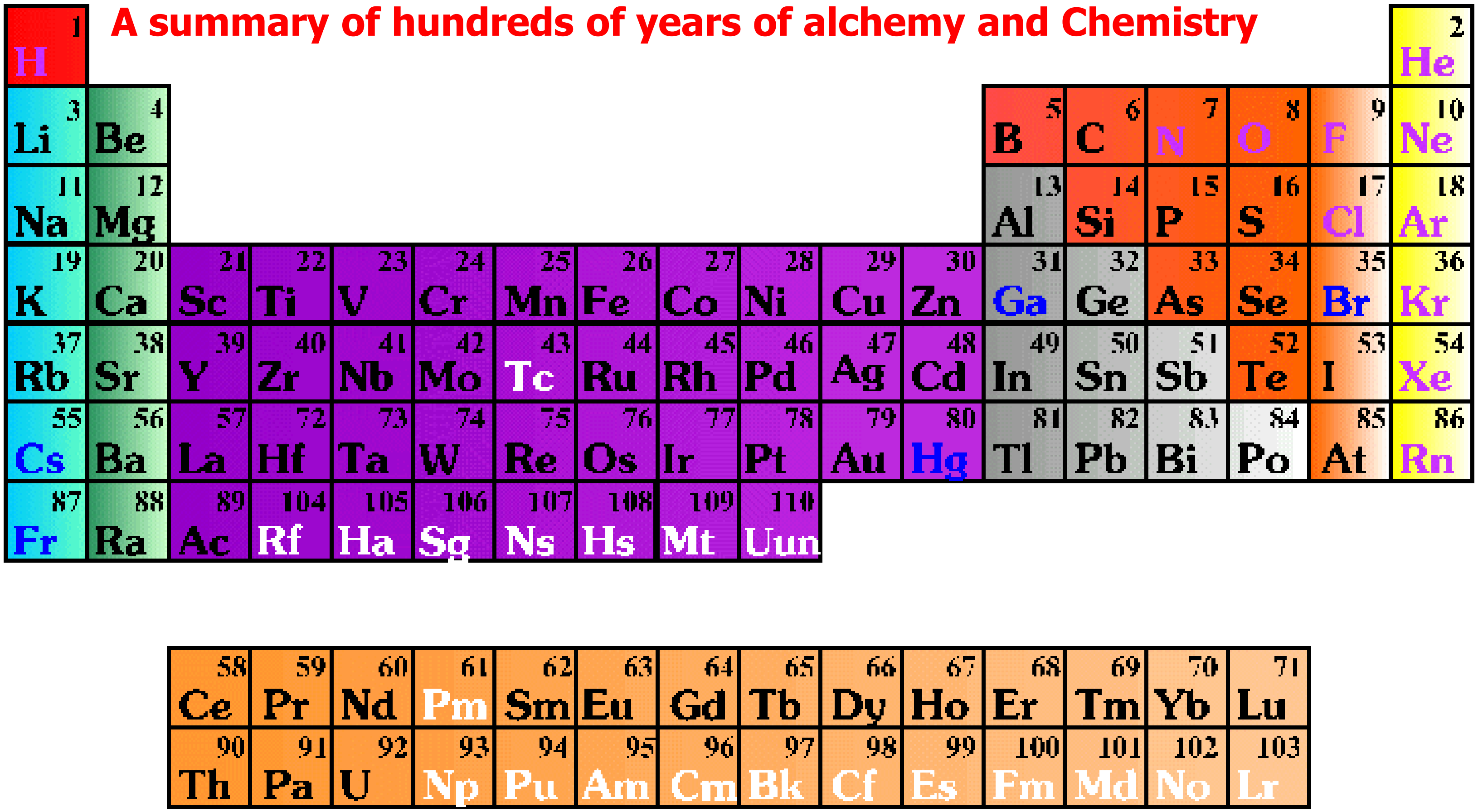
Elementary ≡ Structureless, indivisible

"Time-honored" meaning

Fast-forward to Mid-1800's … to Mendeleyev

The Periodic Table of Elements

A summary of hundreds of years of alchemy and Chemistry



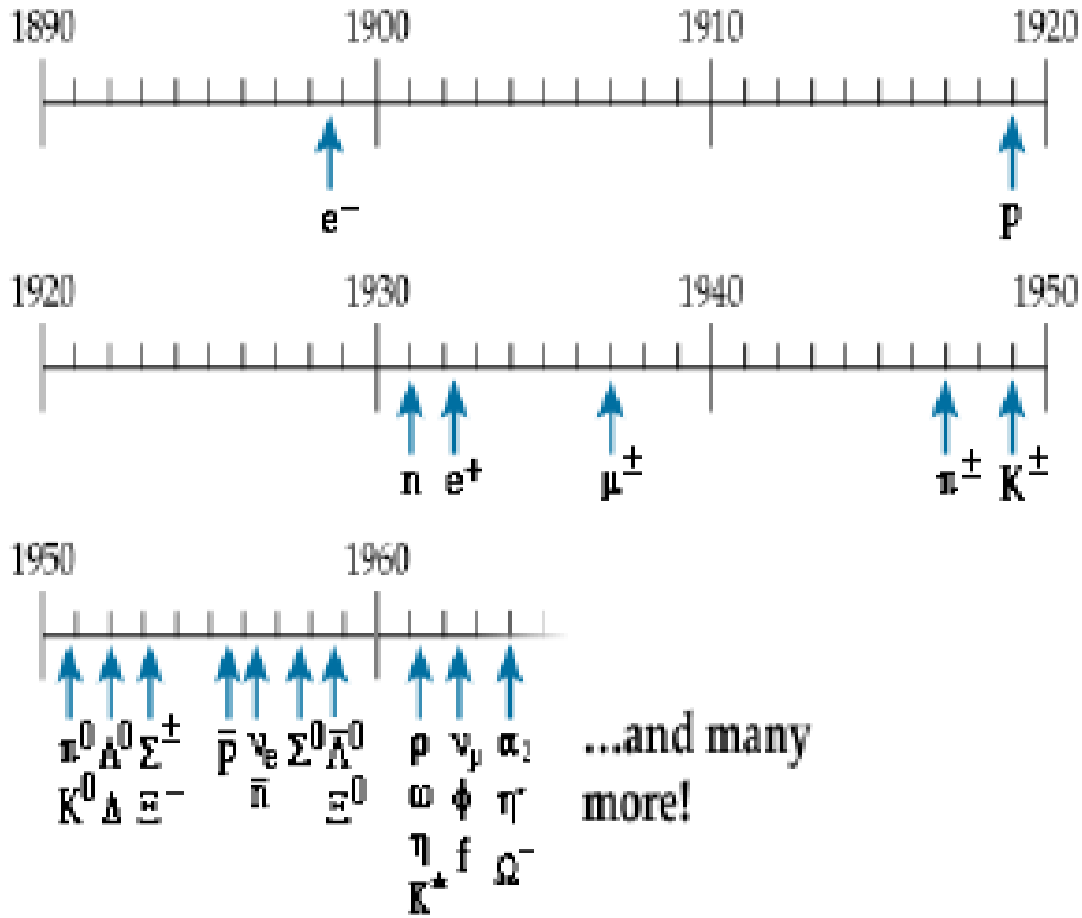
The Modern Atom

- Detailed understanding of the atom began about 50 years after Mendeleyev
- Discovery of the electron, Thompson 1897
  - first elementary particle
- Discovery of the nucleus, Rutherford 1911
  - From scattering alpha particles off of gold foil
- Rudimentary atomic model, Bohr, 1913
  - The atom with a central nucleus and electrons in orbits
- Proton (1919), Neutron (1932)

The saga continues …

With the invention of particle detectors such as the Cloud Chamber and photographic emulsions, many particles were discovered in the study of cosmic rays

Then came the particle accelerators enabling the creation in our own laboratories of such new particles and others unknown, here on earth.

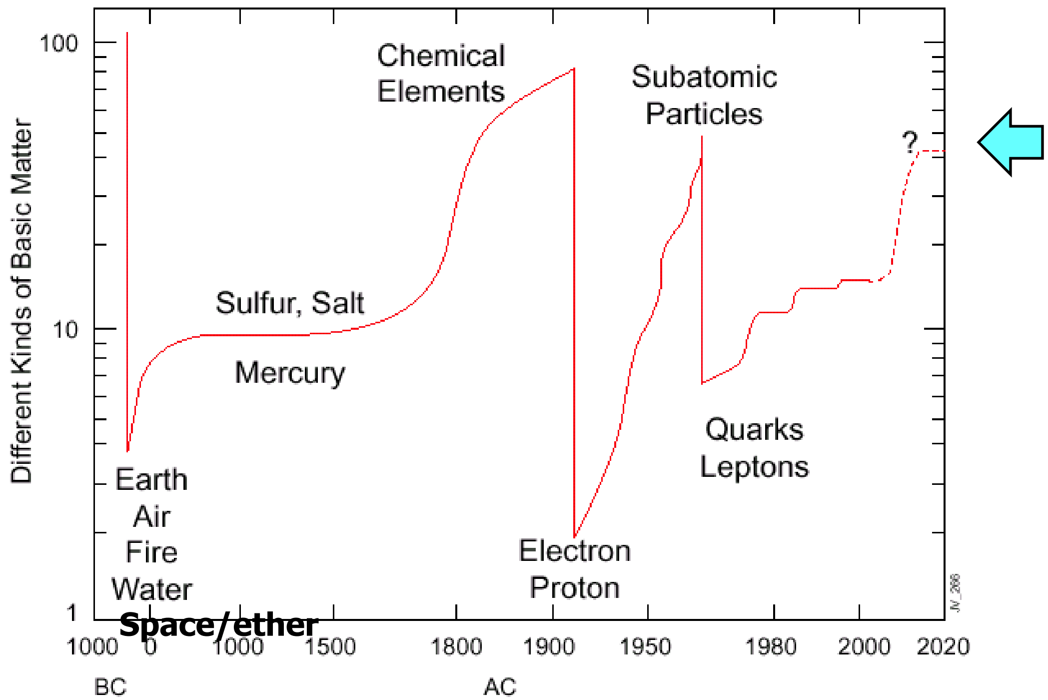


"Three quarks for a muster mark" - James Joyce, Finnegan's Wake

- Colliding protons with nuclei of atoms, using the new particle accelerators, led to the discovery of a large number of new and unanticipated particles
- The complexity hints that the situation is similar to what we had with molecules
- Gellmann explains a plethora of particles using sophisticated mathematical symmetry groups and predicts unseen particle the "Omega"
- Gellmann and Zweig hypothesize the next layer of hadronic matter → "Quarks" (Experimentally demonstrated in late 1960's and early 1970's)

History of

Constituents of Matter



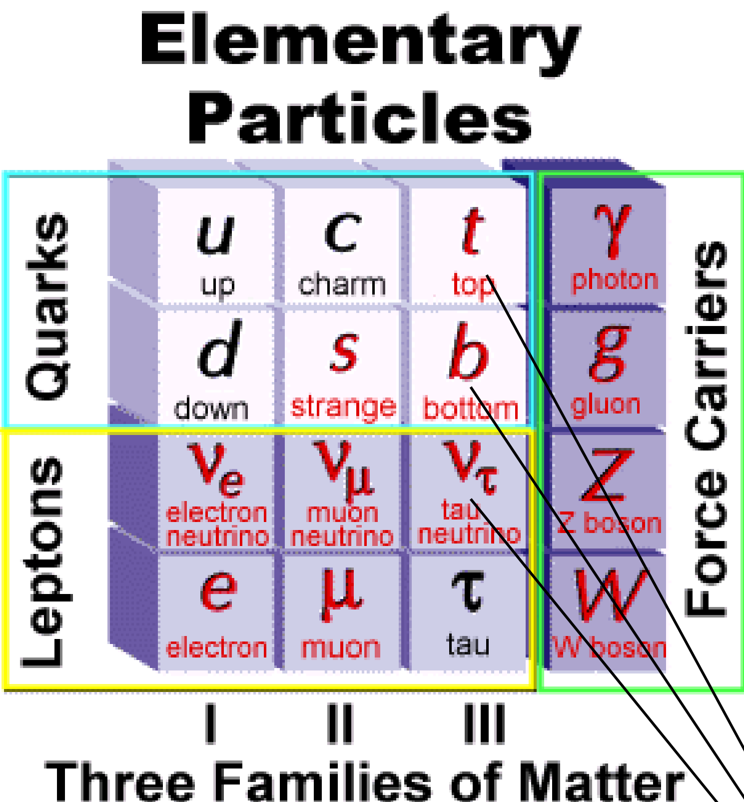
Including hypothesized super-symmetric particles

- What is "Elementary" at the present time may be dependent on experimental resolution and thus subject to revision.
- But, the interactions among elementary particles of the moment is much simpler than their composites.

More than necessary?

- Even though up and down quarks, the electron and its neutrino were sufficient, we kept finding others
- Muons in cosmic rays, 1937
- “Strange” particles containing “strange” quarks
- The November Revolution, 1974:
  - Charmonium (containing Charm quarks) discovered at Brookhaven and at Stanford Linear Accelerator Center
- The “tau” lepton, 1975 (SPEAR/SLAC)
- The “beauty” or “bottom” quark, Fermilab, 1977
- Then, after a long break and heroic efforts worldwide --- The famous “top” quark, 1995, Fermilab
- The “tau neutrino”, 2000, Fermilab

Our Current Lego Blocks
The Standard Model Particles

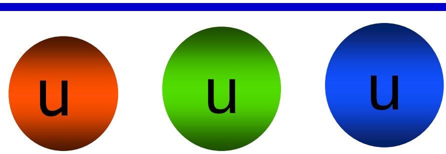


Three generations of quarks and leptons, "elementary", i.e., structure-less, point-particles down to at least 10^{-19} m

And, there is the Higgs which gives mass to the particles

The basic building blocks of "our world" are the first generation particles! The other generations are copies only differing in mass.

SM: Quantum field theories for 3 forces: strong, electromagnetic and weak



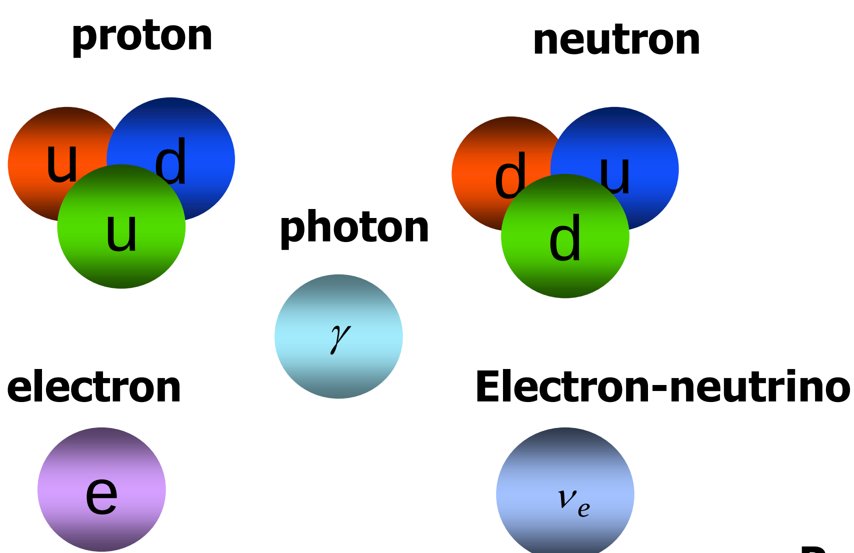
Each type of quark comes in three colors: R, G, B

Three out of four 3rd generation particles discovered at Fermilab

Matter

Anti-Matter

- Everything in our world is made up of First generation particles.
- And, there is also anti-matter!



For every type of particle there exists an antiparticle type

$$i\hbar\frac{\partial}{\partial t}\Psi(\boldsymbol{r},t) = H\Psi(\boldsymbol{r},t) = \frac{\hbar}{i}c\boldsymbol{\alpha}\cdot\vec{\nabla} + \beta mc^2$$

Dirac equation, which we will return to, later.

Positron discovered by Anderson in 1933

The Matter particles

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

The Force Carriers

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

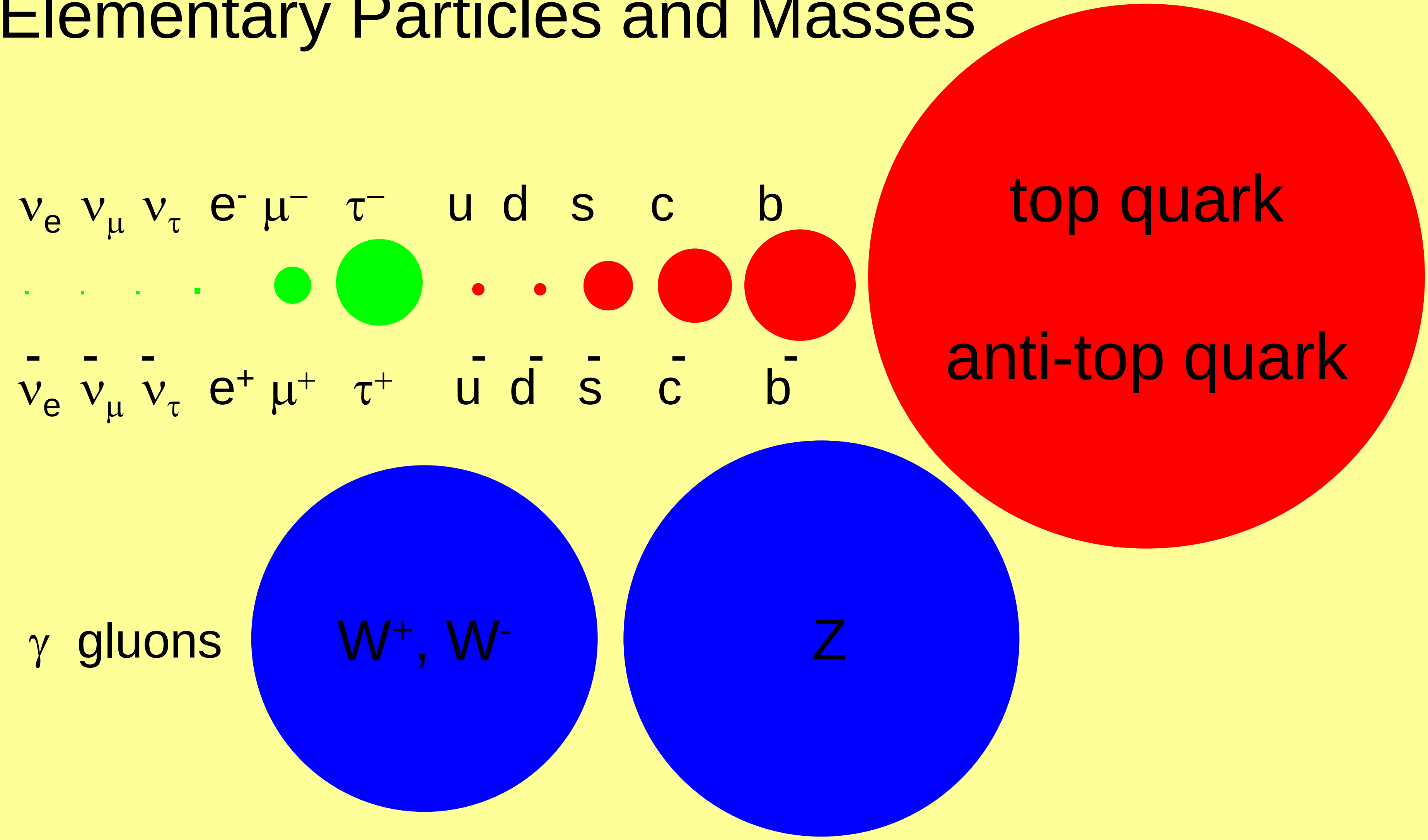
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Eight gluons of different Color-anticolor combinations

Massive

Gravity → Graviton: G → Spin =2, Electric charge=0, Mass = 0

Elementary Particles and Masses



(Mass proportional to area shown: proton mass =)

Are they the smallest things?

Why are there so many?

Where does mass come from?

Standard Model Particles

- Free quarks have not been observed ← Only composites of quarks are observed. This is due to the nature of strong interactions.
  - Mesons ← $Q\bar{Q}$ ← have spin $=n\hbar$
  - Baryons ← QQQ ← have spin$=(2n+1)\hbar/2$

  The composites, hadrons, are color singlet states.

  Quarks behave as free particles within hadrons. But, they are confined within hadrons. (Top quark decays as a free quark once it is produced – no time to hadronize. We will talk about the Top quark later.)
- Leptons exist as free particles. But only loosely bound and unstable lepton system, such as positronium, e+e-, are seen.
- Fermions (quarks and leptons) obey Fermi-Dirac statistics, i.e., the wave-function is anti-symmetric w.r.t. interchange of two identical particles. i.e., two fermions cannot exist in the same quantum state. Pauli exclusion principle.
- Gauge bosons follow Bose-Einstein statistics. The wave-function is symmetric w.r.t. such interchange.

Why We believe in Quarks

- Because of a variety of experimental evidence
  - Protons have point like constituents ➔
  - Spin = ½
    - **Angular distribution of $e^+e^- \rightarrow$qqbar consistent with spin = ½ ; and other measurements**
  - Fractional electric charge

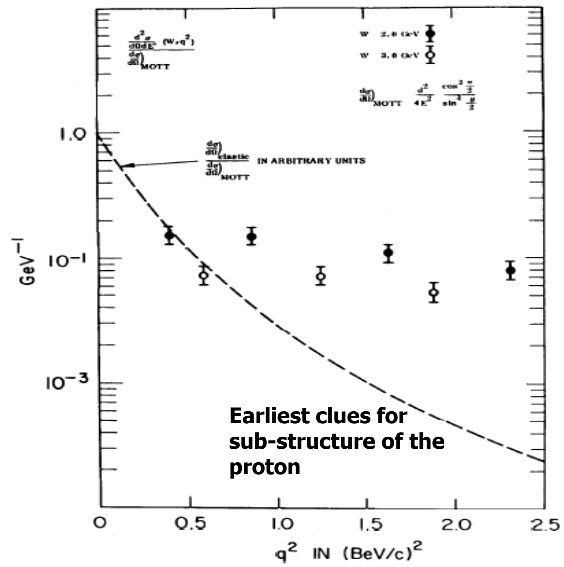


Fig. 11. Inelastic data for $W = 2$ and 3 GeV as a function of q^2. This was one of the earliest examples of the relatively large cross sections and weak q^2 dependence that were later found to characterize the deep inelastic scattering and which suggested point-like nucleon constituents. The q^2 dependence of elastic scattering is shown also; these cross sections have been divided by σ_M

- $$\frac{\sigma(\pi^+ C \rightarrow \mu^+\mu^- + X)}{\sigma(\pi^- C \rightarrow \mu^+\mu^- + X)} = \frac{1}{4}$$

$$\because\ \pi^+ = u\bar{d} \quad \sigma(\pi^+ C \rightarrow \mu^+\mu^- + X) \propto e_d^2 \ \text{ Since } d\bar{d} \rightarrow l^+l^- \quad \leftarrow \left(\frac{1}{3}\right)^2$$

$$\& \quad \pi^- = \bar{u}d \quad \sigma(\pi^- C \rightarrow \mu^+\mu^- + X) \propto e_u^2 \ \text{ Since } u\bar{u} \rightarrow l^+l^- \quad \leftarrow \left(\frac{2}{3}\right)^2$$

  - **Ratios of decay rates of vector mesons (ρ,η, ϕ, etc)**

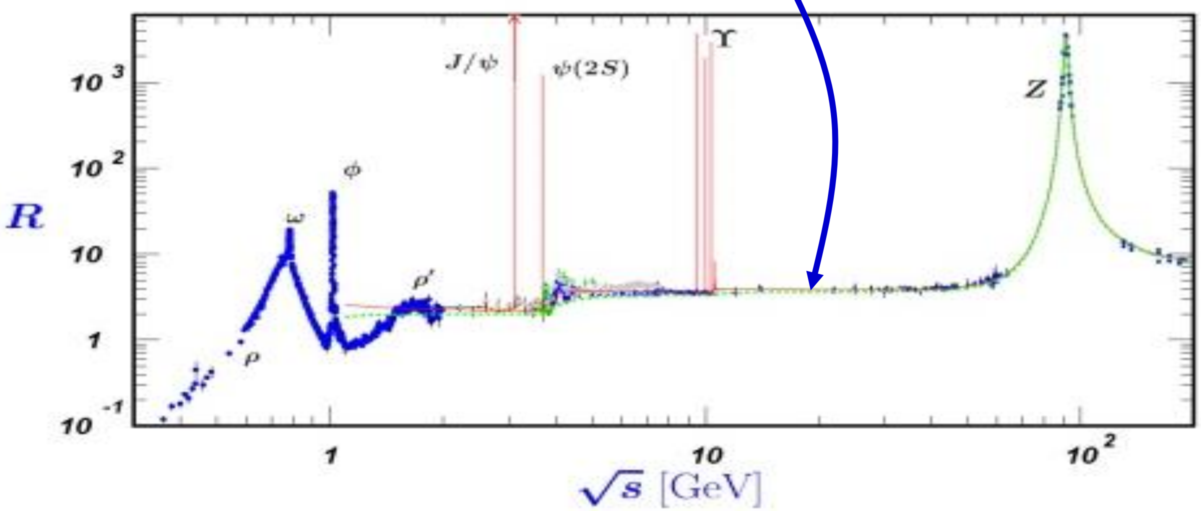
$$\Gamma(V^0 \rightarrow l^+l^-)$$

Why We believe in Quarks

- Evidence for three colors

  - $$R = \frac{\sigma(e^+e^- \to Hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3 * \sum_{u,d,c,s,b} Q_i^2$$

$$= \frac{11}{3}$$



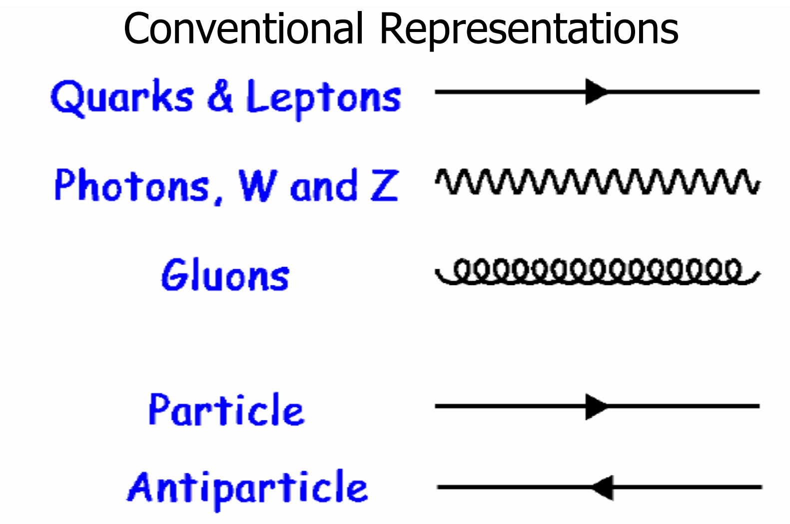
Fundamental Forces

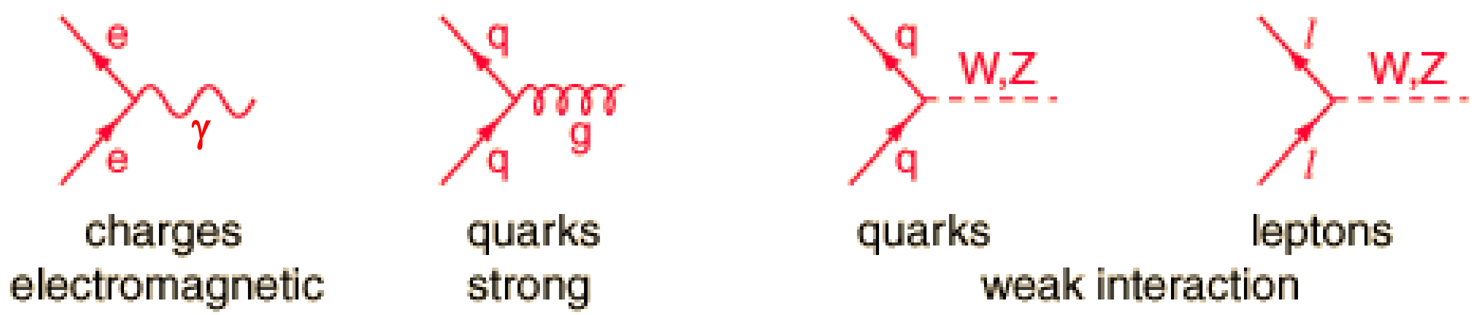
Interaction	Gravity	Electro-magnetic	Weak	Strong
Field quantum	Graviton	Photon	Intermediate bosons $W^{\pm}$, Z^0	Gluon
Spin-parity	2^+	1^-	$1^-, 1^+$	1^-
Mass (mc^2), GeV	0	0	80–90	0
Range, m	∞	∞	10^{-18}	$\leq 10^{-15}$
Source	Mass	Electric charge	"Weak charge"	"Color charge"
Coupling	K (Newton)	—	G (Fermi)	—
Dimensionless coupling constant	$KM^2/\hbar c = 0.53 \times 10^{-38}$	$\alpha = e^2/4\pi\hbar c = \frac{1}{137}$	$(Mc/\hbar)^2 G/\hbar c = 1.02 \times 10^{-5}$	$\alpha_s \sim 1$, large r < 1, small r
Typical cross-section, m^2 (1 GeV)	—	10^{-33}	10^{-44}	10^{-30}
Typical lifetime for decay, s	—	10^{-20}	10^{-8}	10^{-23}

- **Gravity is extremely weak at all energy scales we are concerned with.**
- **No complete and consistent theory of gravity. String theory is one of the candidates.**

Particle Interactions & Feynman Diagrams

- Feynman diagrams are fantastic tools for graphically representing particle interaction processes and for performing calculations
- The interactions occur by the emission and absorption of gauge bosons at the "vertices"





Note alternate convention for W,Z

But, the story maybe just beginning

- We thought we have learnt so much … but it turns out we have known only 4% of what makes the universe
  - The remaining stuff: Dark Matter, Dark Energy
- SM is a beautiful, remarkably successful theory but there are things it does not explain
- There must be new physics beyond the SM

Is Nature SuperSymmetric?

- A postulated symmetry between bosons and fermions:
  - all the presently observed particles would have new, more massive superpartners (SUSY is a broken symmetry)

  "Discovery of supersymmetry would begin a reworking of Einstein's ideas in the light of quantum mechanics."

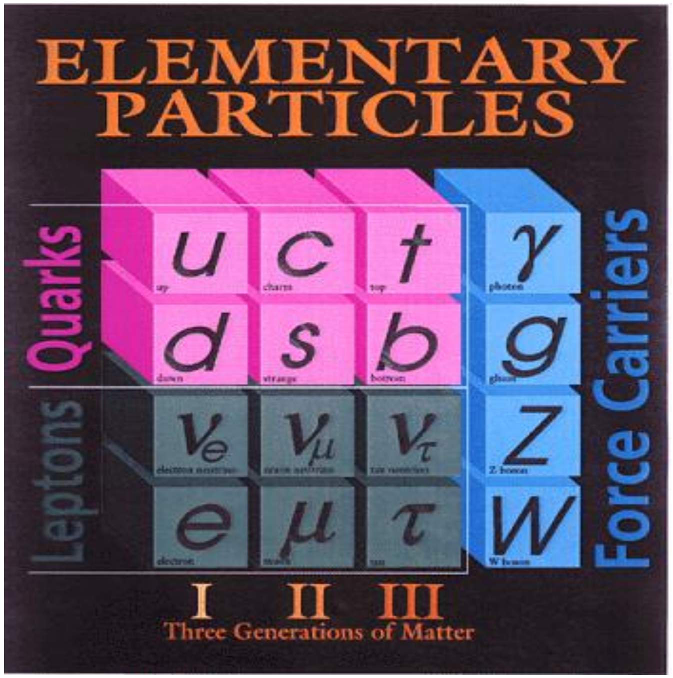
- It is a firm prediction of string theory (the "ultimate" theory?)

- Solves many deficiencies of the Standard Model

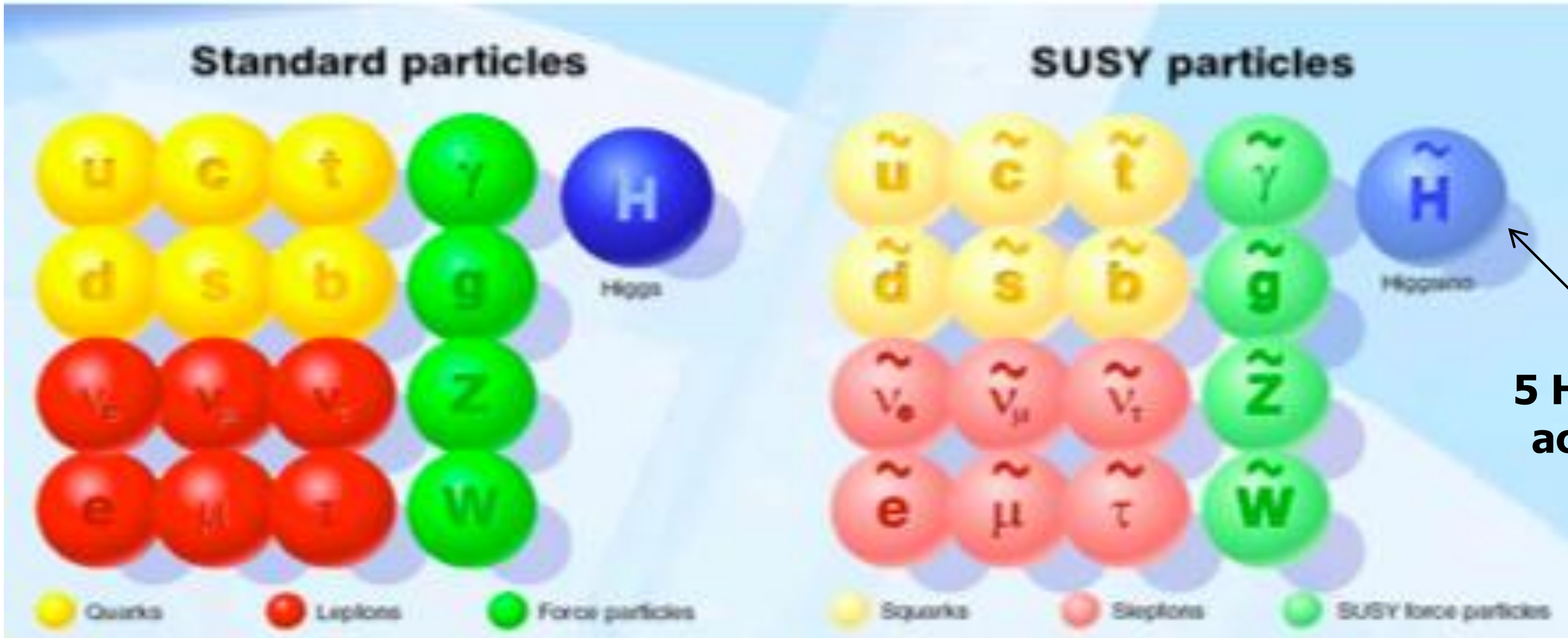
- Does this elegant theory describe nature?

  Only experiment can tell us.

particle	superpartner
quark	squark
gluon	gluino
photon	photino



Susy

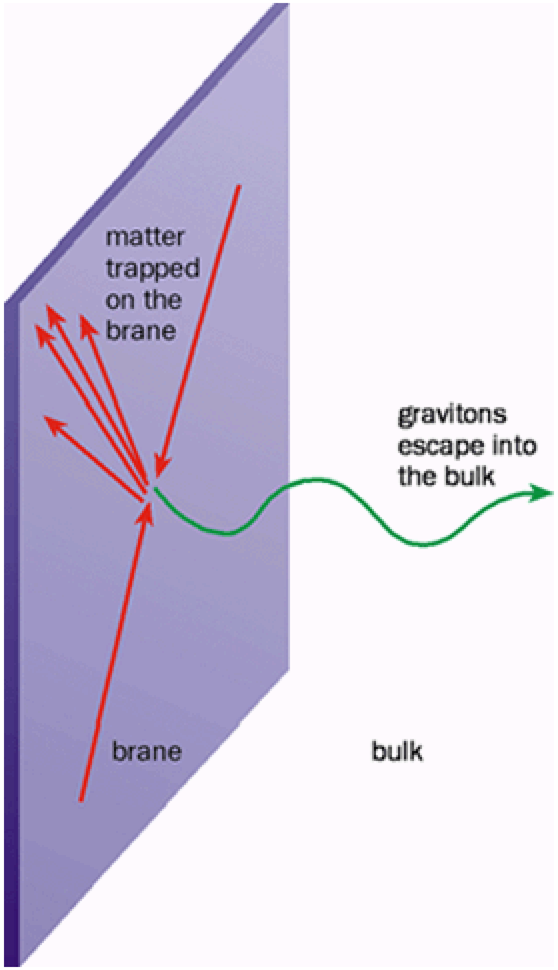


5 Higgses actually

The discovery of "super-matter" can, not only identify a new symmetry in nature duplicating all known forms of matter and mediators of the interactions. There will be implications on cosmology, unification of interactions.
The Lightest Supersymmetric Particle, the neutralino could be a good dark matter candidate. Gas of neutralinos could hold together the cluster of galaxies.
New vision of our universe: improve our understanding from 4% to 30% of the total matter.

Are there Extra Space-time Dimensions?

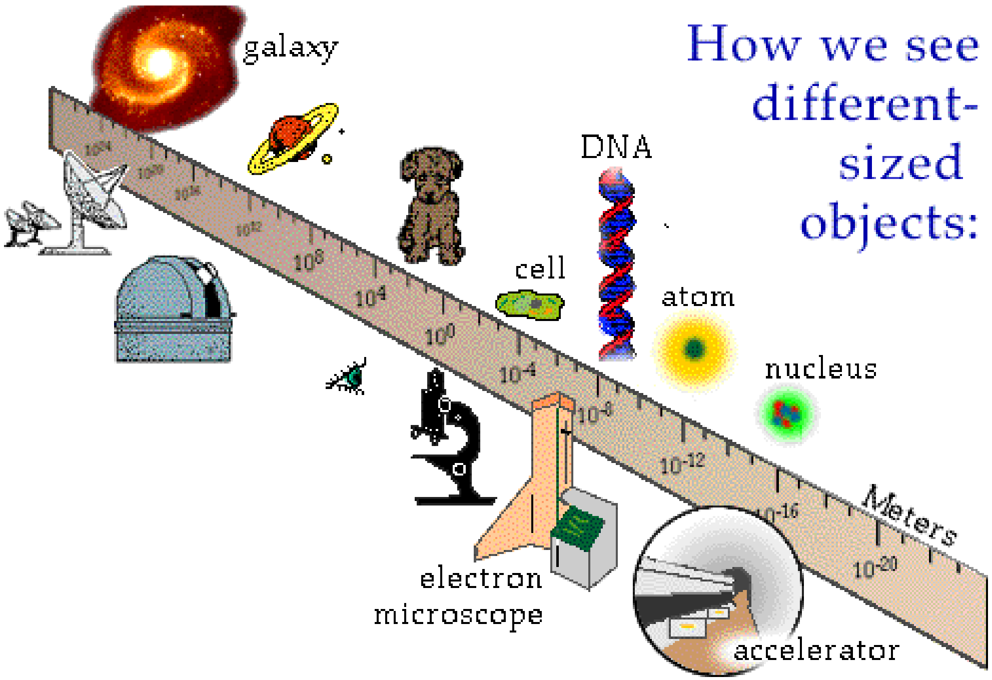
- Why do we think there might be extra dimensions?
  - String theory needs them
  - They can be used to explain why gravity seems weak to us
  - They would also solve other mysteries of particle physics.
- The extra dimensions are hard to see, for some reason. They might be compact and small. If an extra spatial dimension is compact, coiled up with size R, we would see new massive "Kaluza-Klein" particles m=1/R, 2/R, ...
  - We can produce these at colliders if there is enough energy.
- The extra dimensions could be large, but we are trapped on a 3-dimensional membrane in a higher-dimensional space-time.
  - Only gravity acts in the extra dimensions, which can be of macroscopic size.



We desperately need clues from experiments

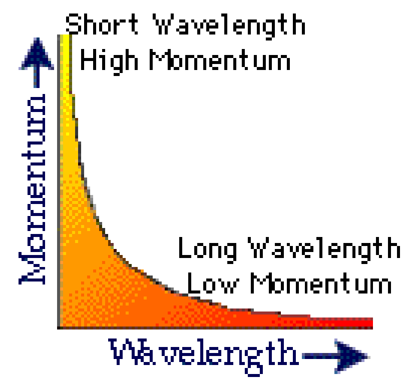
Particle Accelerators

Why High Energy Particle Beams?



De Broglie said moving particles have an equivalent wavelength,

$$\lambda \propto \frac{1}{p}$$



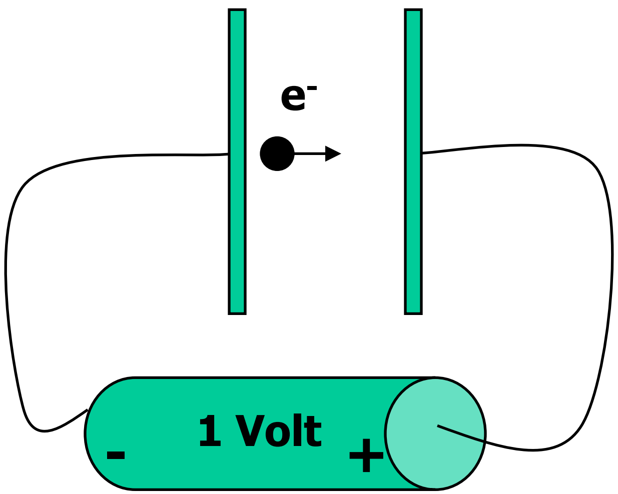
Add a little bit of relativity:

$$E^2 = (mc^2)^2 + (pc)^2$$

High energy gives us high momentum meaning short wavelengths so that we can resolve small distance scales

Particle Acceleration and Energy Units

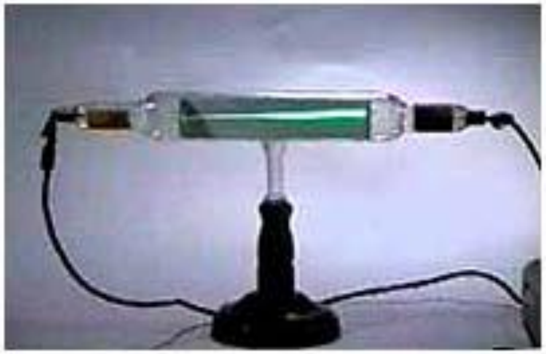
- 1 electron Volt (eV) is the amount of energy gained by a particle with unit charge when it is accelerated across a 1 Volt potential difference



Energy E = 1 eV
= 1.6×10^{-19} J

1 keV = 10^3 eV
1 MeV = 10^6 eV ~ 2 x mass of the electron
1 GeV = 10^9 eV ~ mass of the proton, neutron
1 TeV = 10^{12} eV ~ energy of protons and pbars in the Fermilab Tevatron
Energy density in the Universe at < 10^{-9} sec after the Big Bang

First Laboratory Particle Accelerator



The Cathode Ray Tube

The First Particle Accelerator

J.J. Thomson

Discoverer of the electron (1897)

The First Circular Accelerator

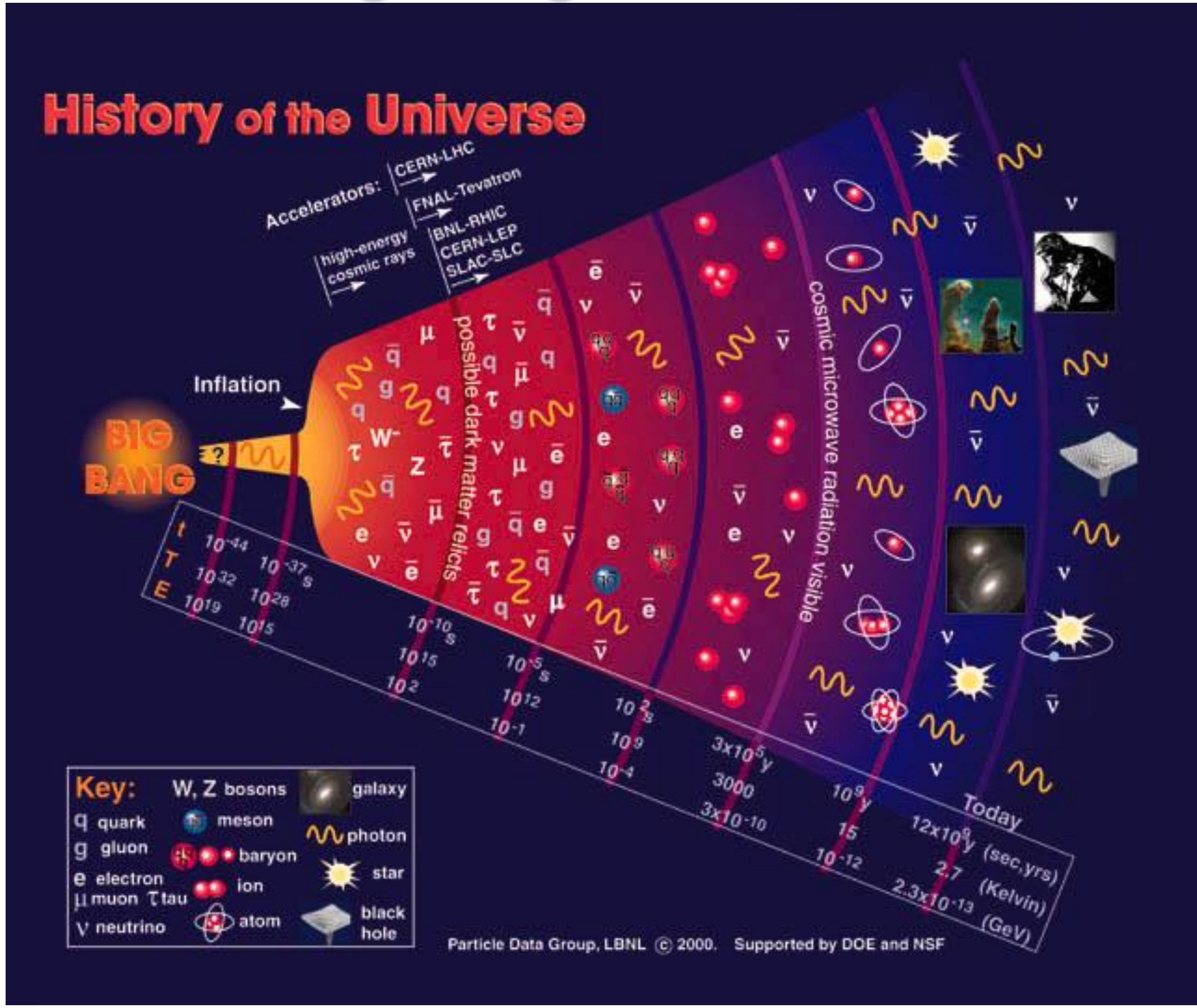
E.O. Lawrence and his first Cyclotron, 1929

The First Particle Physics Experiment: The Big Bang

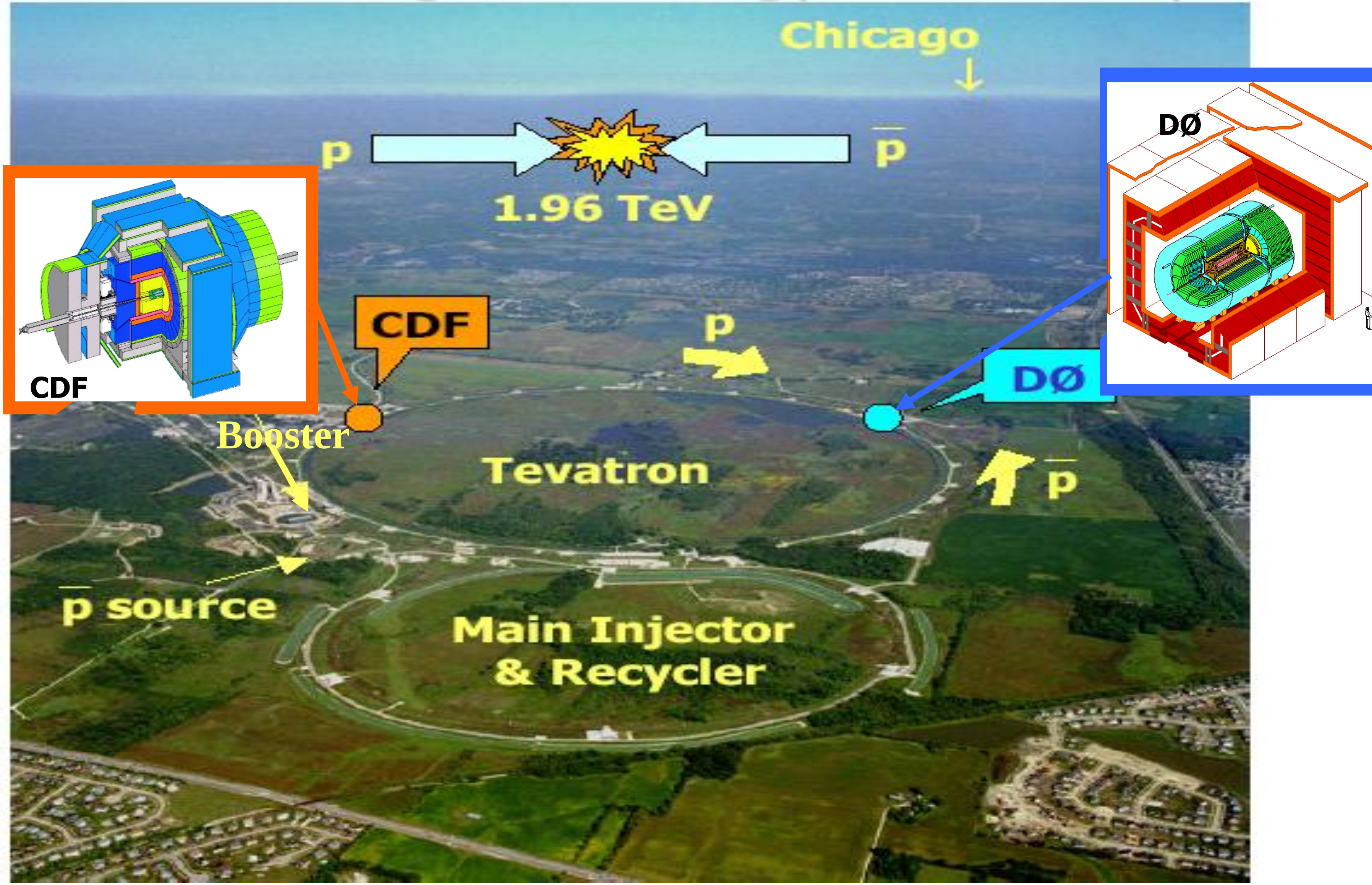
10 microseconds
Quarks form protons.

300,000 years
Nuclei capture electrons and form atoms. The universe becomes transparent.

13,700,000,000 years
Today



World's Highest Energy Laboratory



Tevatron, Batavia -- 1980's
Highest energy to date

Fermilab Accelerators

Accelerator	Maximum Energy (eV)	Velocity (Fraction of the speed of light)	Length (m)
Cockcroft-Walton	750,000	0.012643094	10
Linac	400,000,000	0.713054226	130
Booster	8,000,000,000	0.994475049	477
Main Injector	120,000,000,000	0.999969904	3319
Tevatron	980,000,000,000	0.999999543	6218

Tevatron energy ~ 1 TeV = 10^{12} eV

Large Hadron Collider, CERN
14 TeV C.M. energy

LHC Machine is a marvel of technology

Proton –proton collider

2808 bunches in each beam

Beam Power = 1.6 MJ

To reach the required energy in the existing tunnel, the s.c. dipoles operate at 8.3 T (200,000 x Earth's magnetic field) & 1.9 K in superfluid helium.

Protons travel in a tube with better vacuum and colder than inter-planetary space.

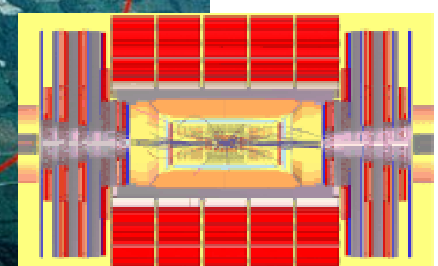
wrt Tevatron (USA)	
Energy (14 TeV)	**x 7**
Luminosity ($10^{34}cm^{-2}s^{-1}$)	**x 30**

The Era of Fermilab

10^{-8} seconds

- Temperature
  1000 trillion K

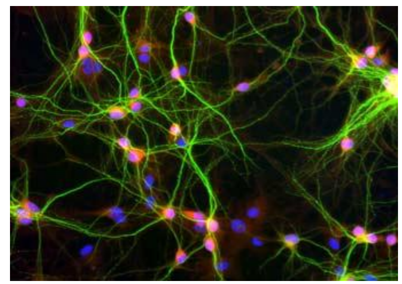
Near Future

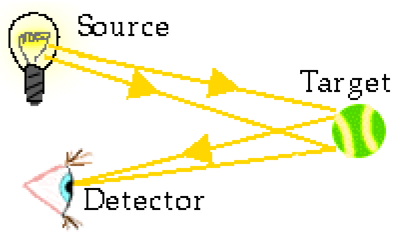


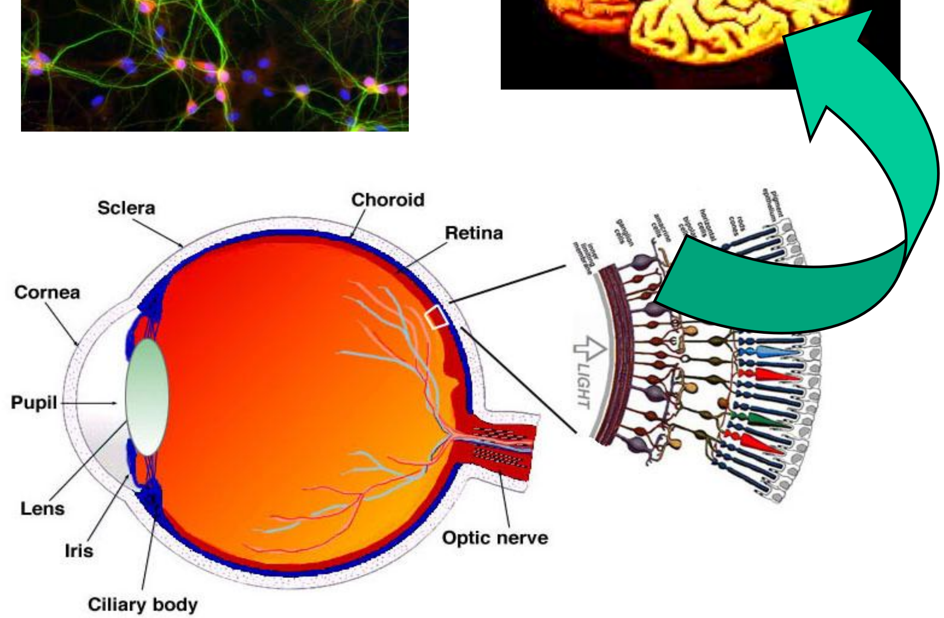
Experiments

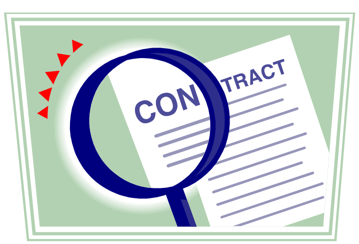
The Process of Observation

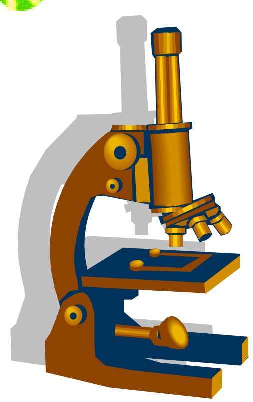
- Eye is an ingenious design of a photon detector, even though it senses only a tiny part of the electromagnetic spectrum! Along with the brain and the connectors forms a complete system for experimental observation and analysis











We need to see more, learn and understand! Augment our eyes and brains!

Global/Composite Detector Systems for HEP

<u>Need to find</u>

–Number of particles

–Event topology

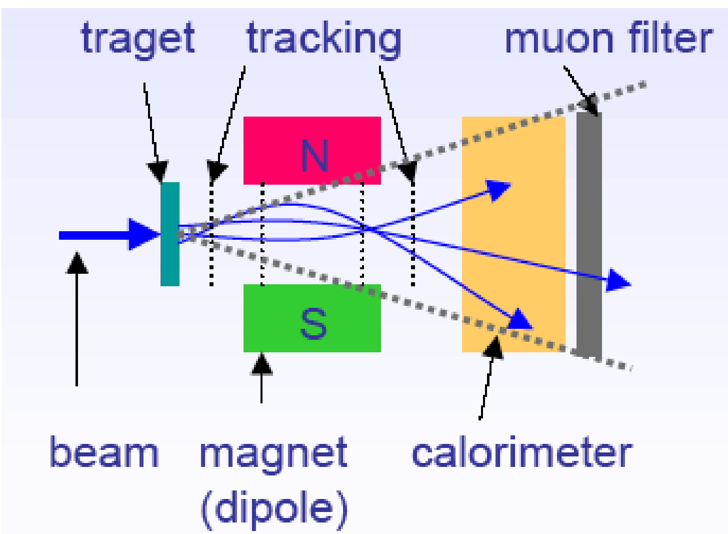
–Momentum/energy

–Particle identity

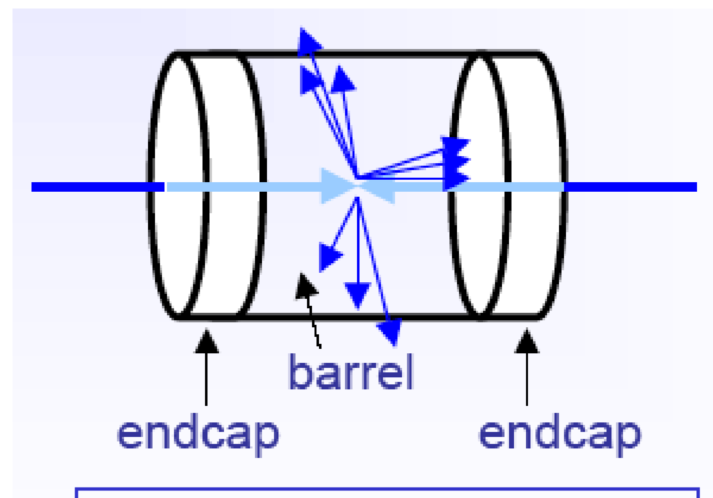
No single detector does it all…

→ Create detector systems

Fixed Target Geometry



Collider Geometry



- “full” solid angle coverage

Fermilab E831 FOCUS

Charm Photoproduction   Precision study of charm decays

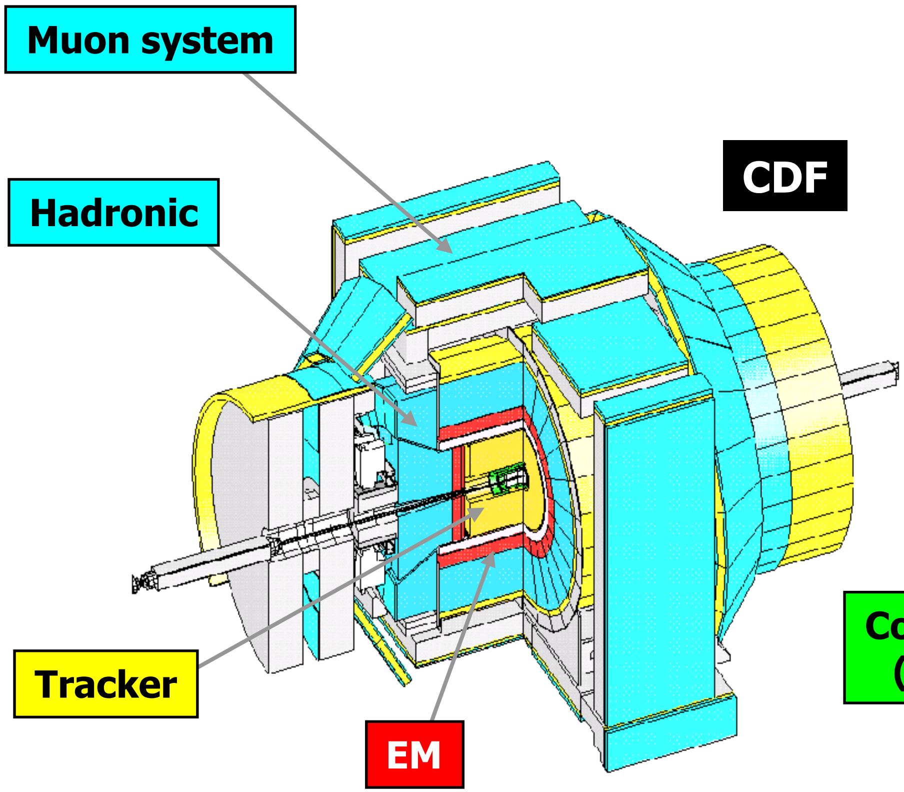
Silicon, Scintillation, cerenkov detectors, drift chambers, etc.

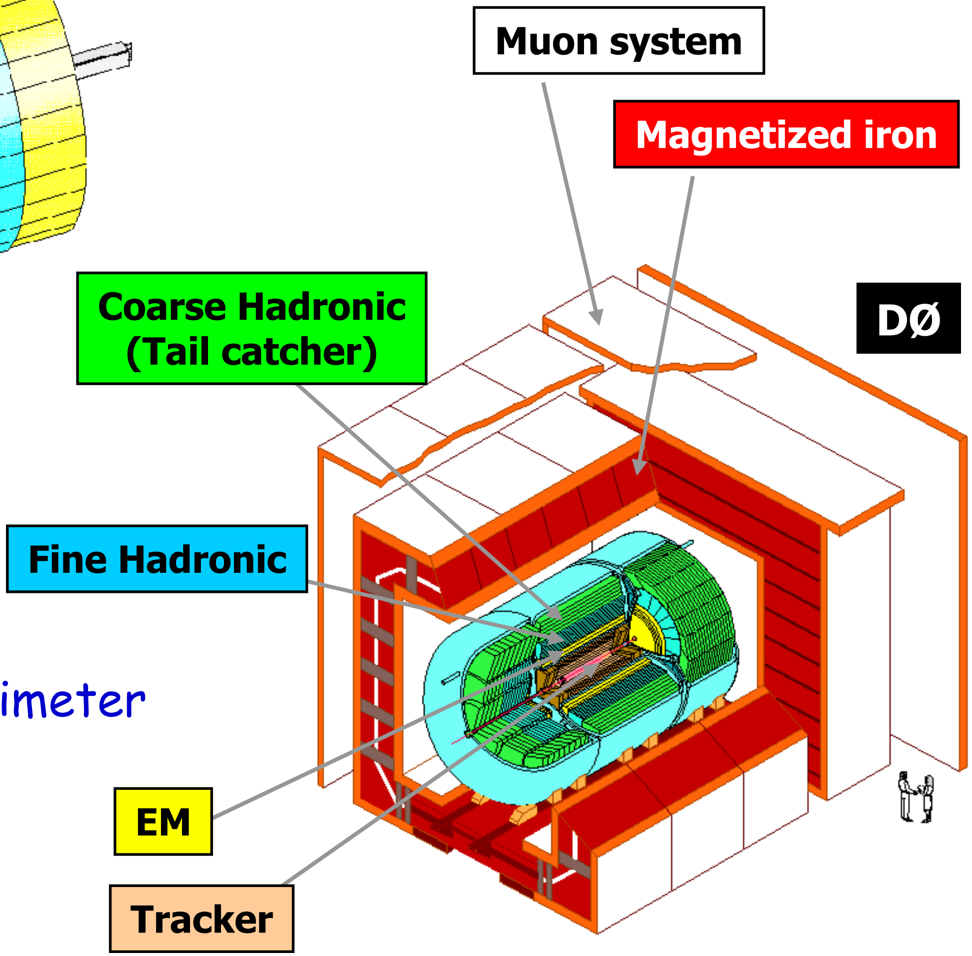
Miniboone, Fermilab

Spherical Tank (12 m dia) filled with mineral oil and equipped with photomultiplier tubes

Looking for neutrino oscillations

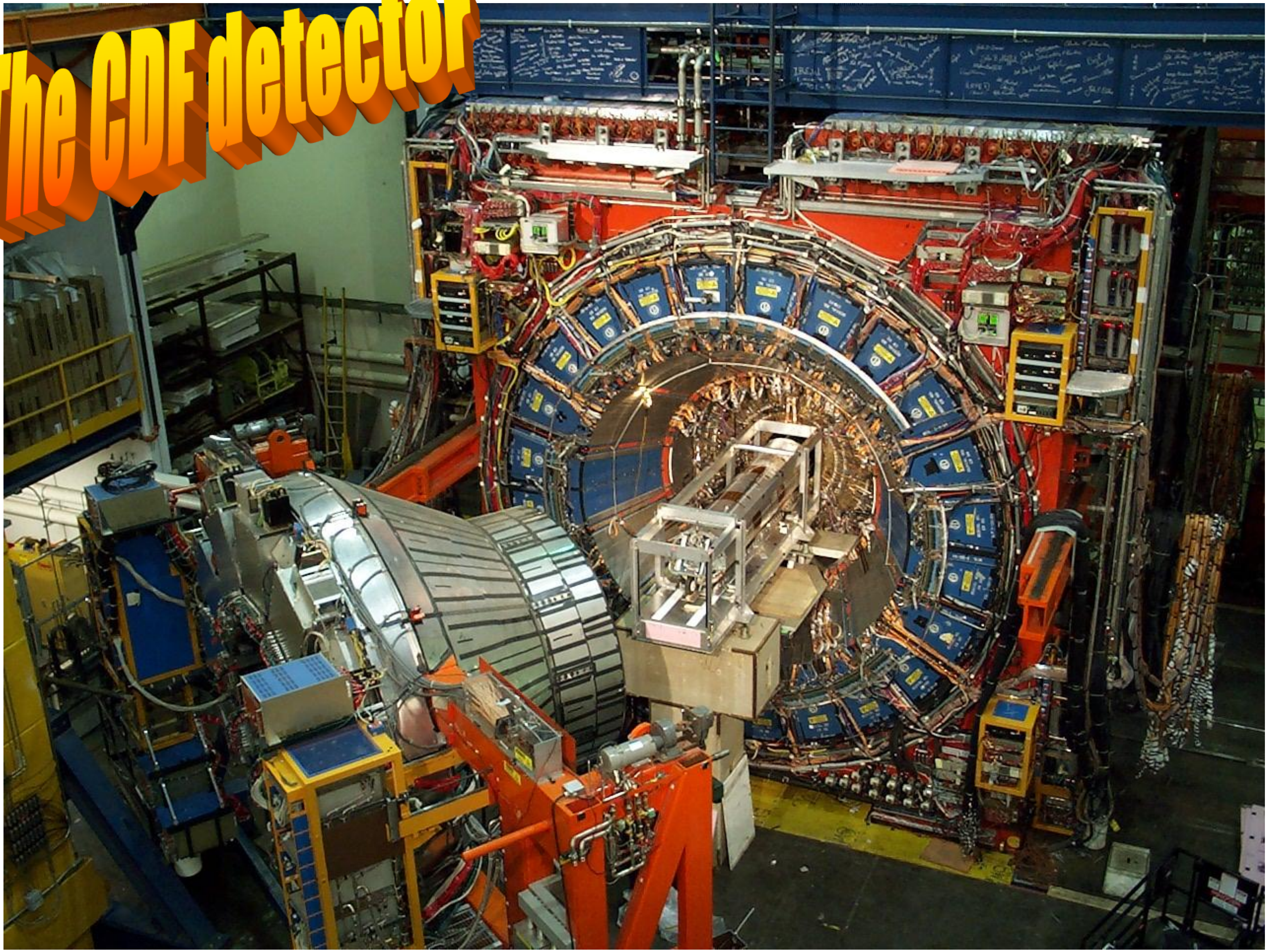
Arrays of sensitive instrumentation
> Million electronic channels each





- "Transparent" central tracking in a magnetic field
- Energy measurement of photons, electrons and hadrons in the calorimeter (most particles absorbed)
- Muons measured in the outermost magnetic spectrometer
- Missing energy (neutrinos) from measuring everything else

The CDF detector

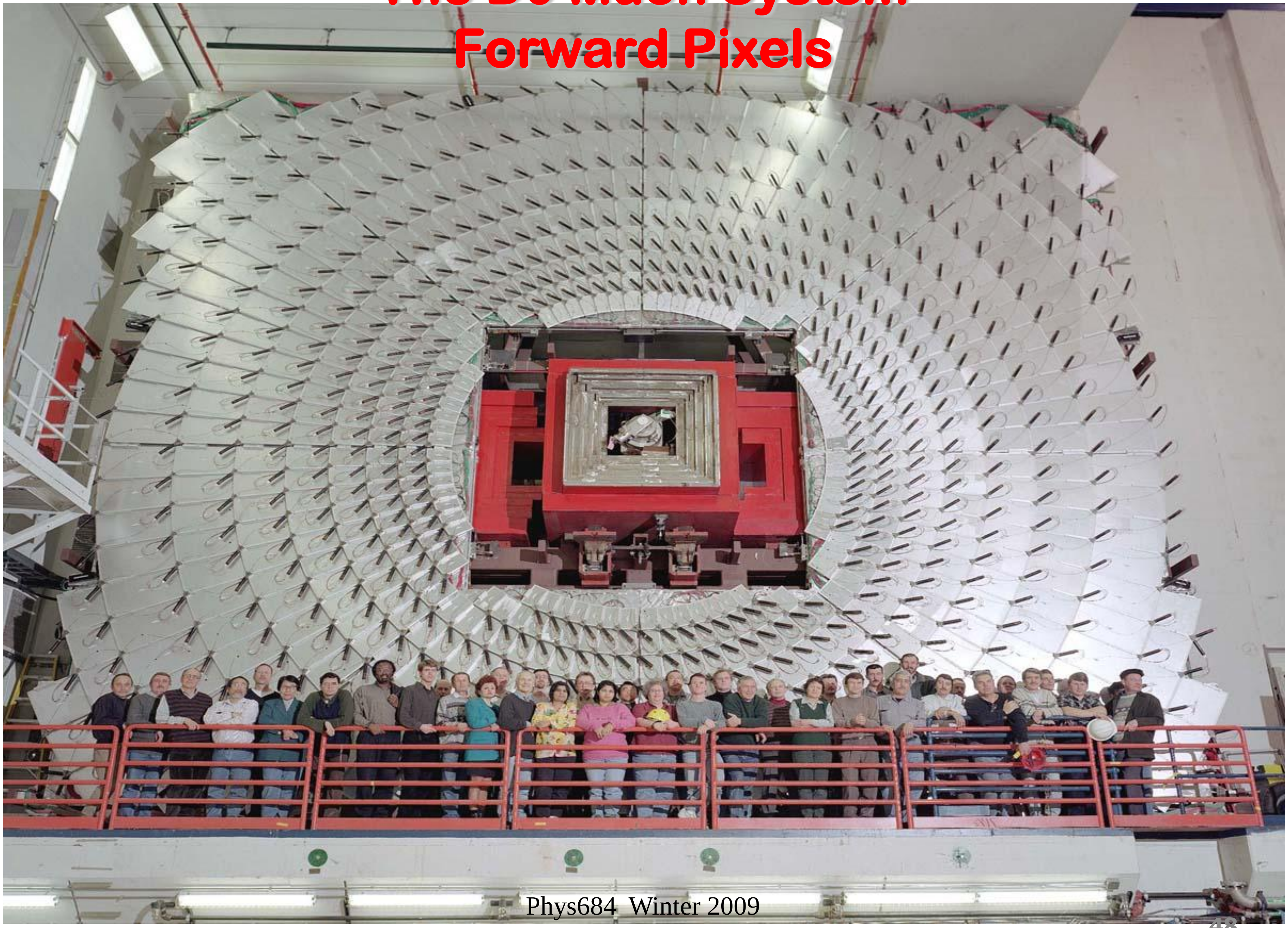


Installing silicon tracker, prior to CDF detector roll-in

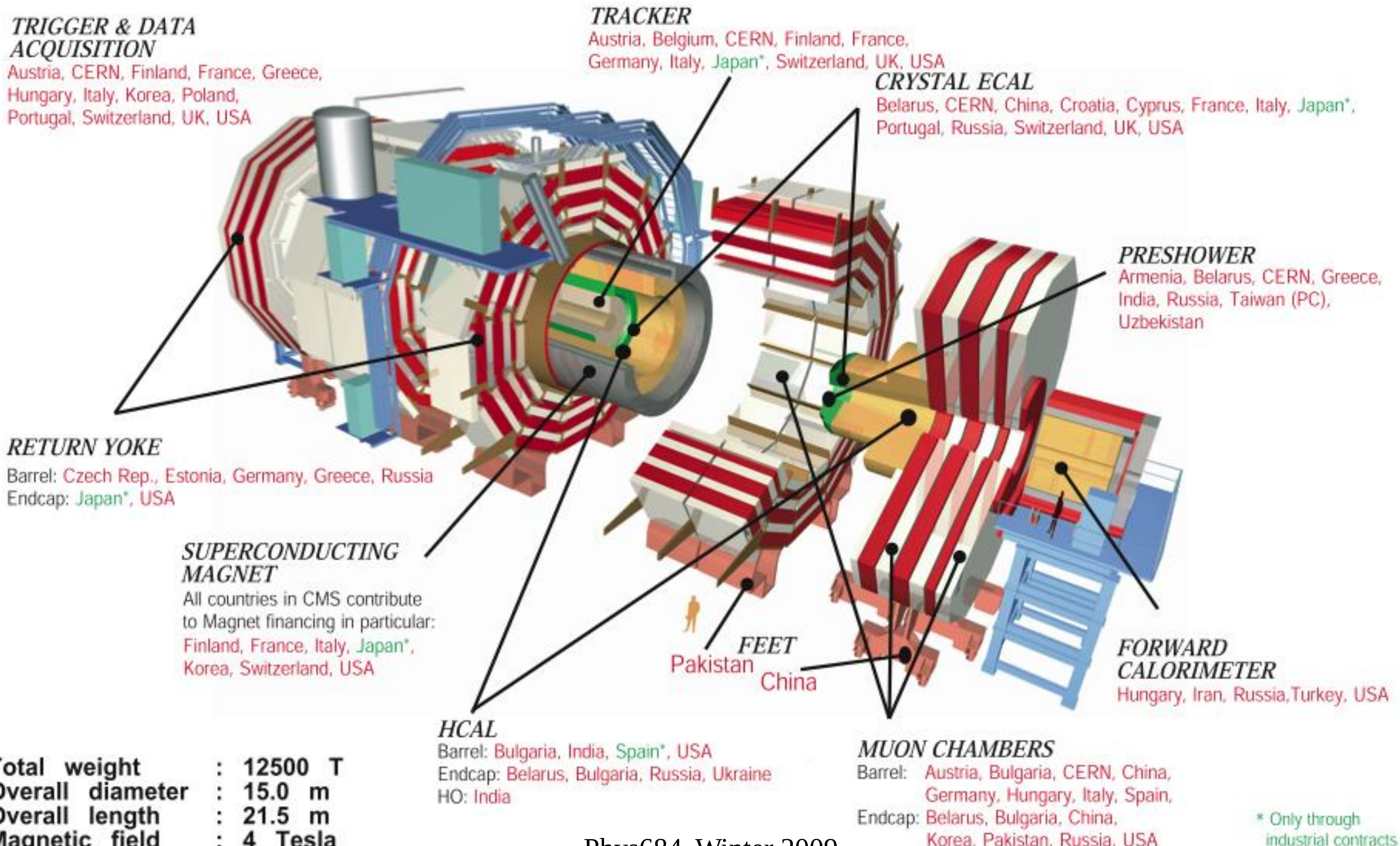
The DZero Detector

DØ detector installed in the Collision Hall, January 2001

The D0 Muon System
Forward Pixels



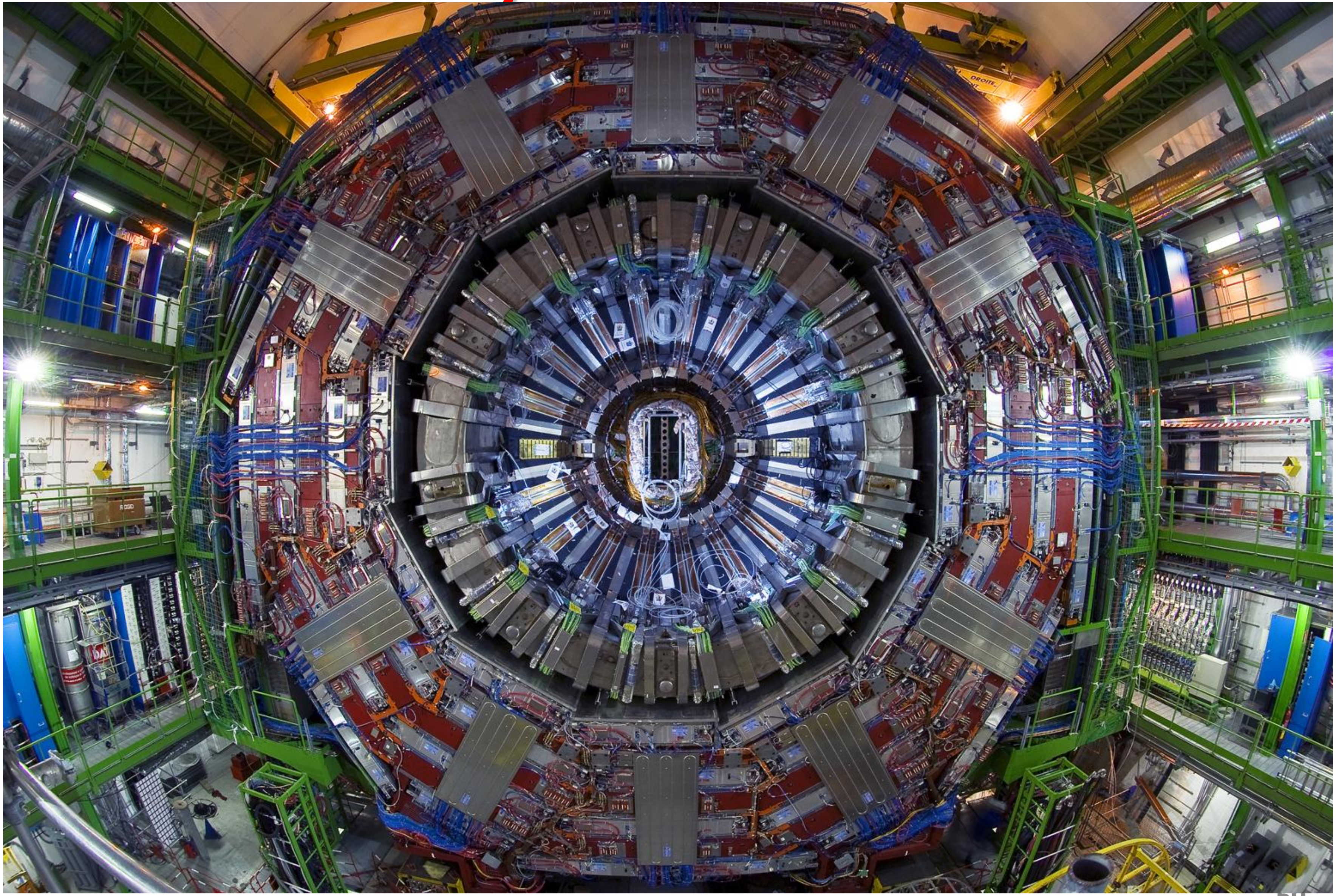
CMS at CERN



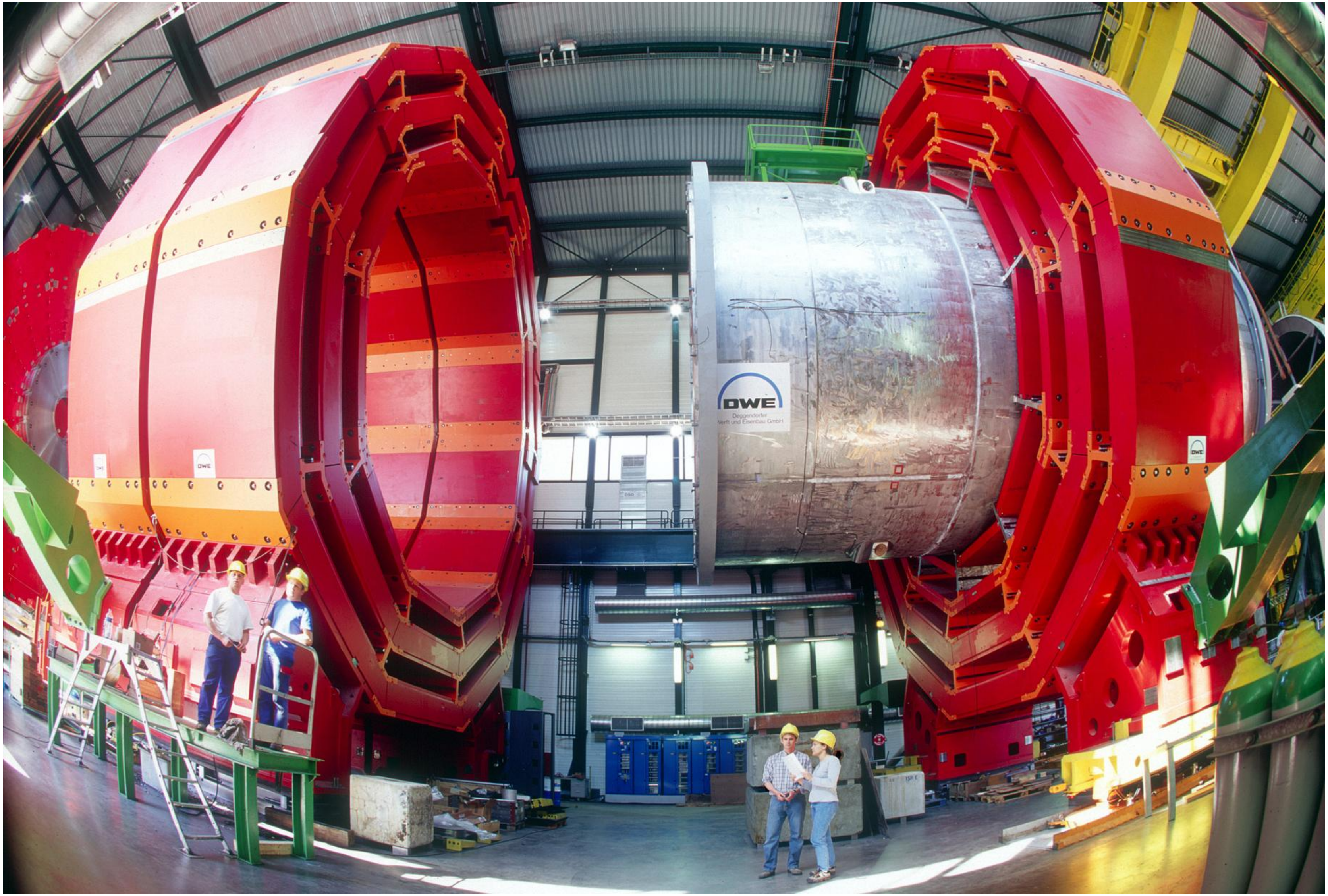
Total weight	**:**	**12500 T**
Overall diameter	**:**	**15.0 m**
Overall length	**:**	**21.5 m**
Magnetic field	**:**	**4 Tesla**

Solenoid

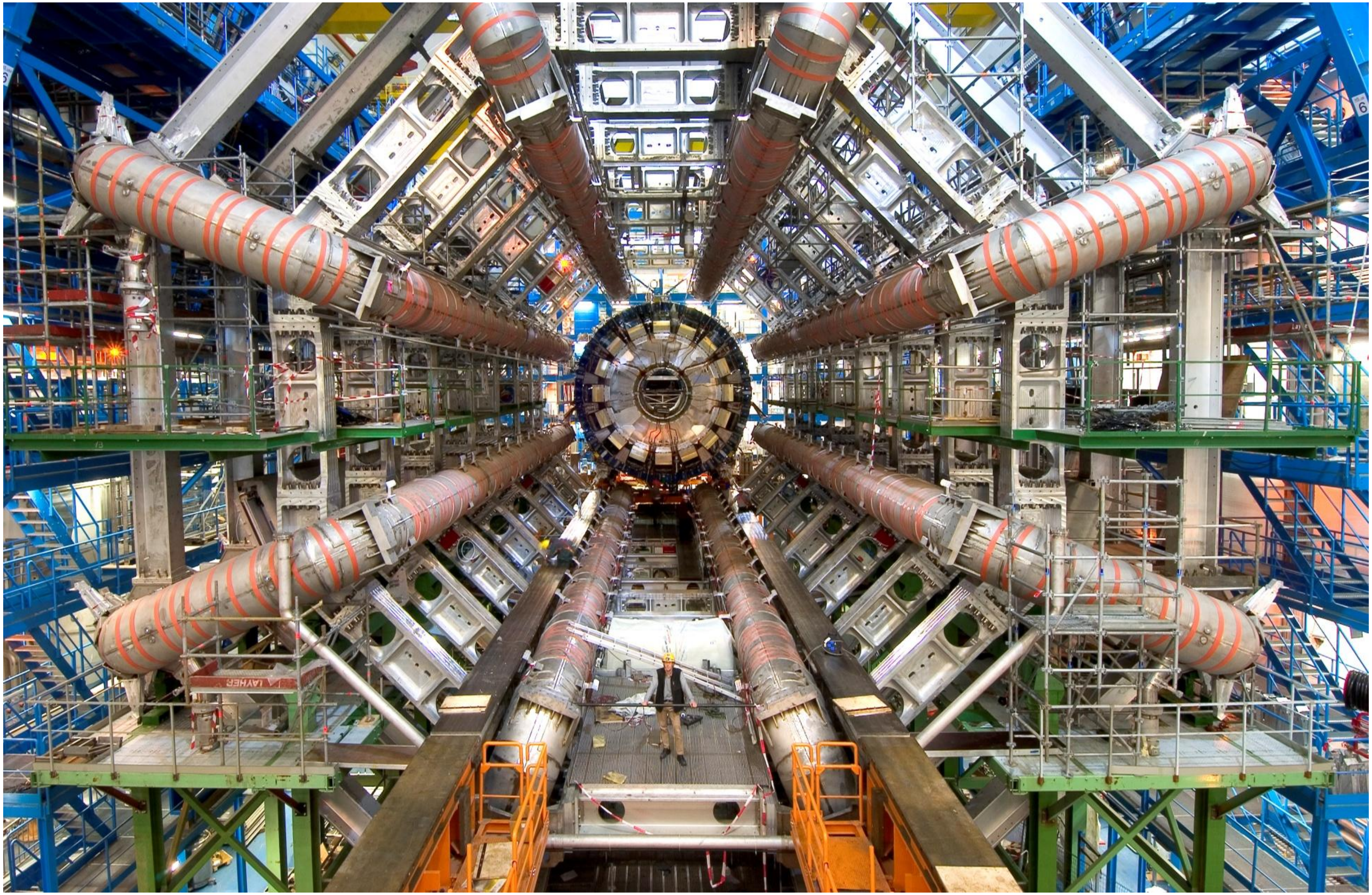
Fisheye View of CMS



CMS Magnet Yoke Assembly



ATLAS



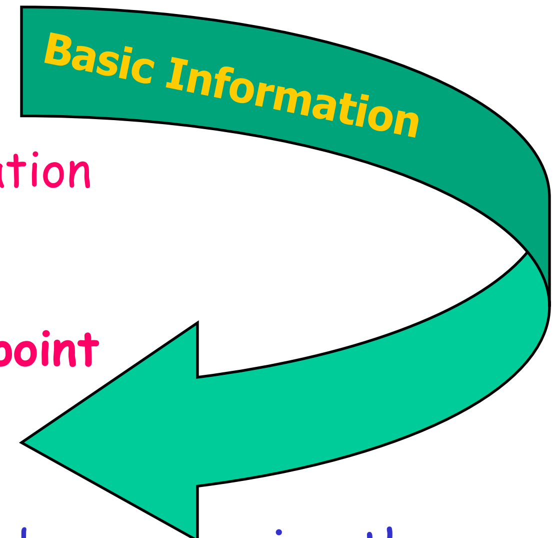
Particle Detectors as Active Cameras

- To learn about what happens in high energy collisions, we need to track, identify and measure particles produced
  - Very large, Multi-layered, multi-system detectors surrounding the interaction region
  - Fine granularity → millions of readout channels
  - Fast readout electronics
  - Complex, multi-tier data-acquisition systems
  - Huge computing needs for data processing

Identify and Measure Particles

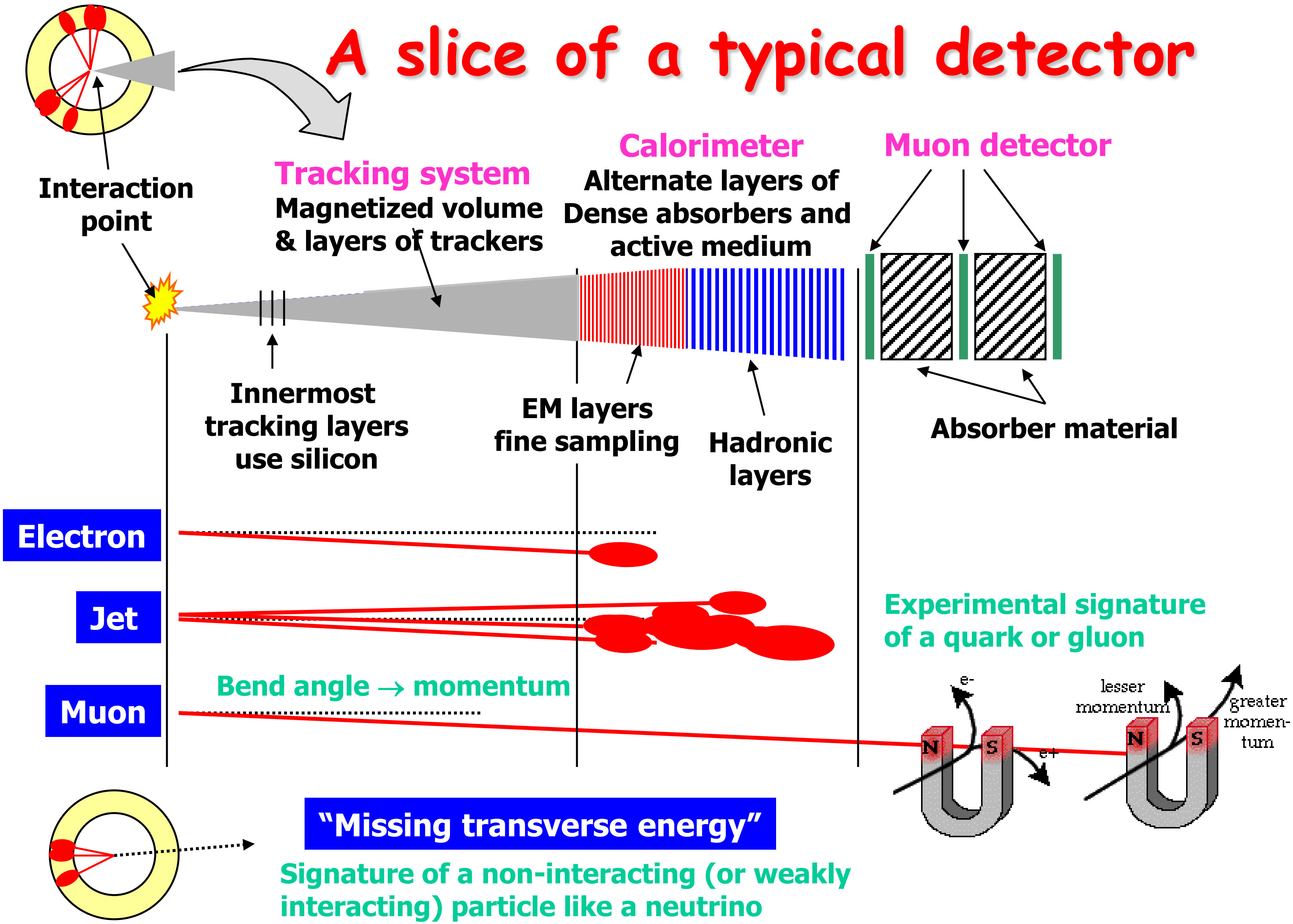
- Detectors should
  - Track, match and count particles
  - Measure energy/momentum
  - Find particle identity
  - Measure charge
  - Measure missing energy
  - Provide full solid angle coverage, fine segmentation
  - Have fast response, ideally zero deadtime

  ⇒ **Many kinds of detectors → sub-systems with several layers surrounding the collision point**



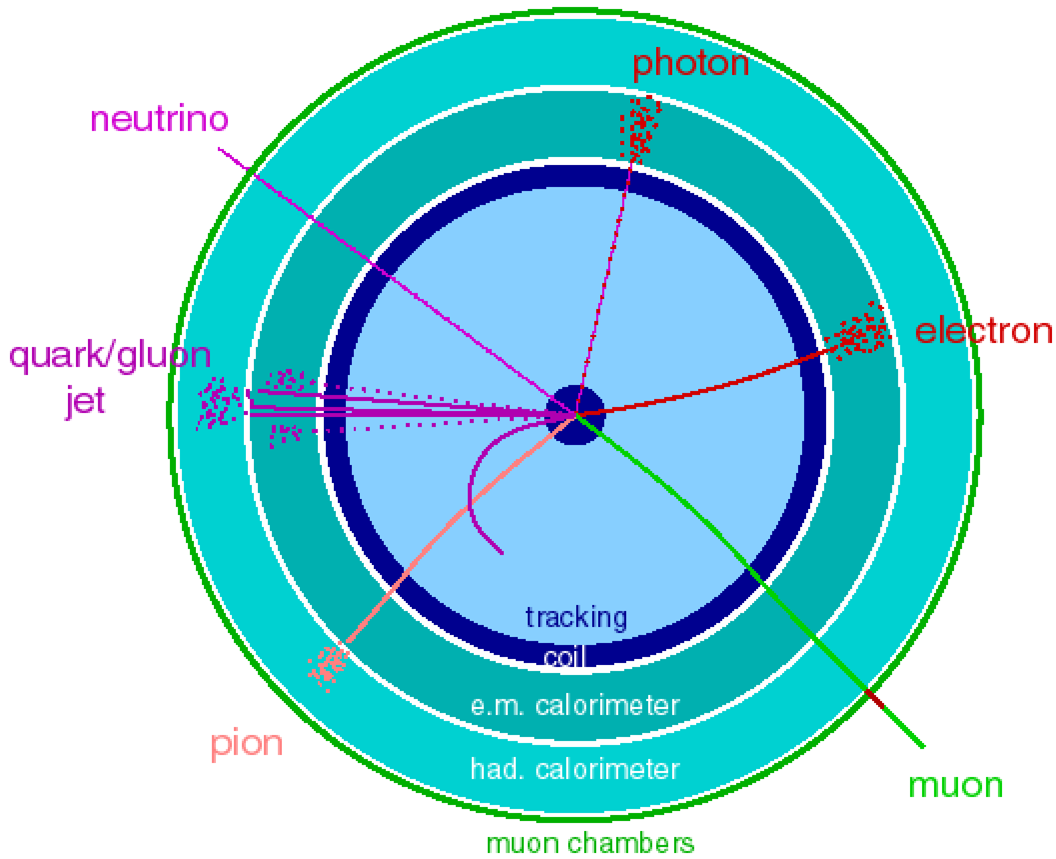
- Find Collision vertex
- Find and measure short-lived parent particles by measuring the children
- Perform analysis to understand the process that produced the event

A slice of a typical detector



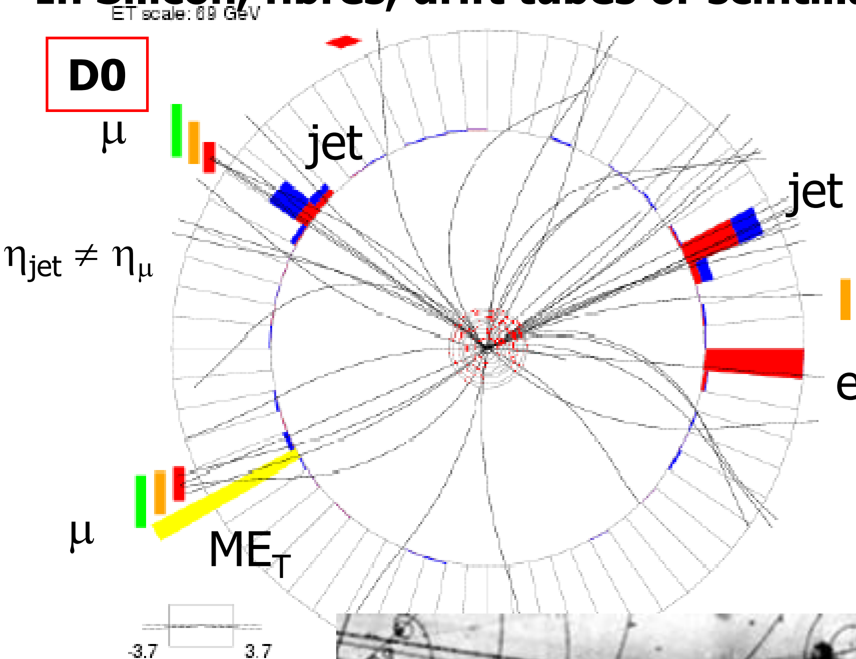
TYPICAL Collider Detector

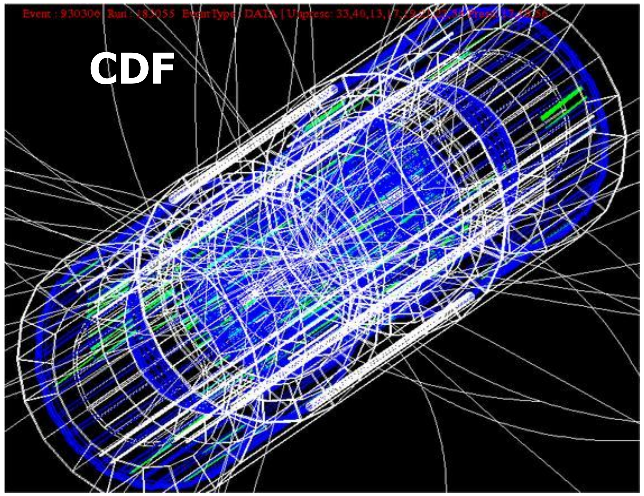
Cross sectional View

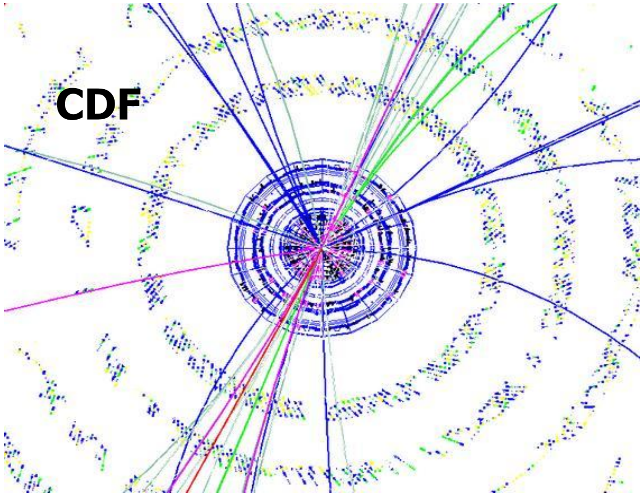


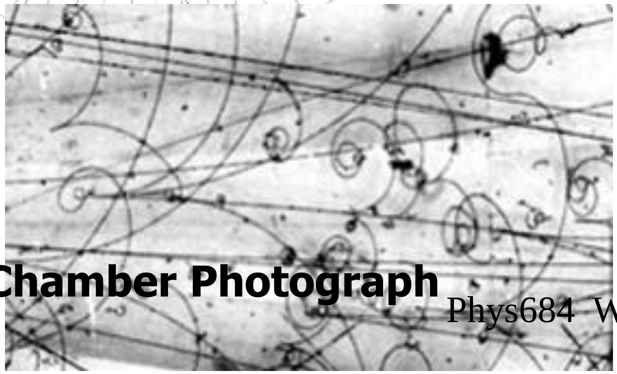
Tracks Reconstructed

Modern trackers:
Tracks reconstructed from electronic signals (hits) from the readout cells
In Silicon, fibres, drift tubes or scintillators

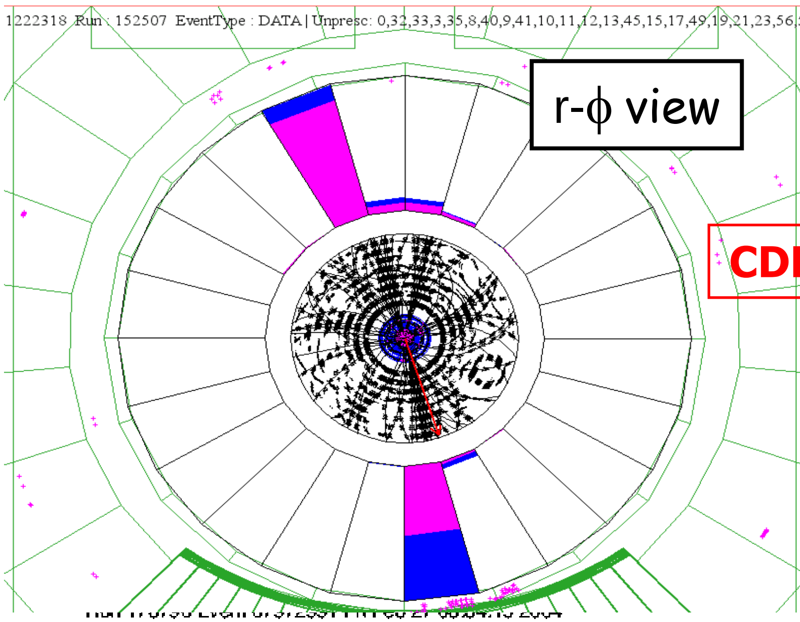




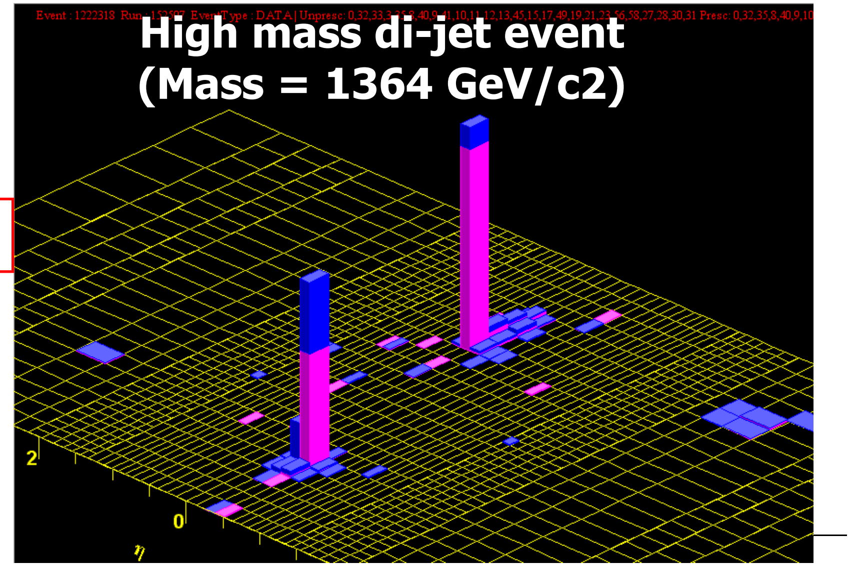


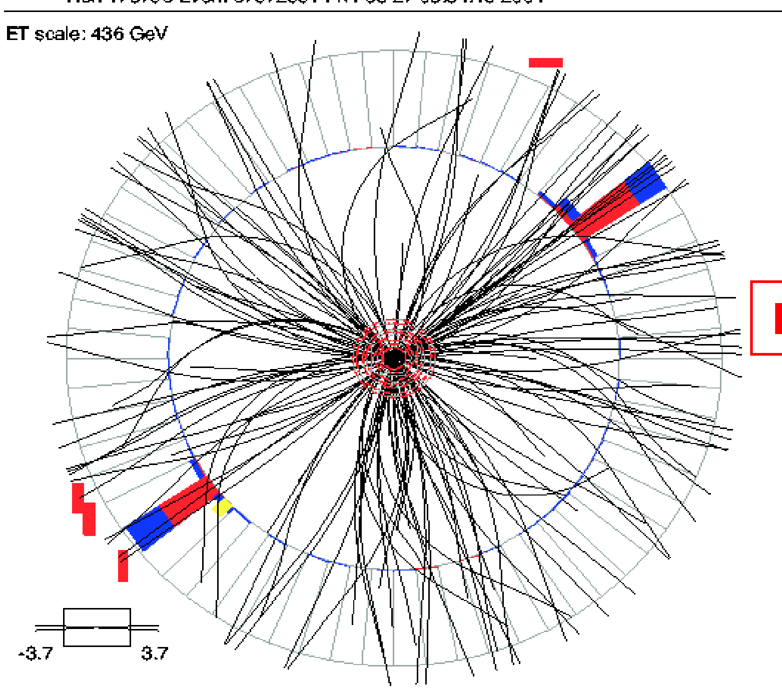


Old Bubble Chamber Photograph

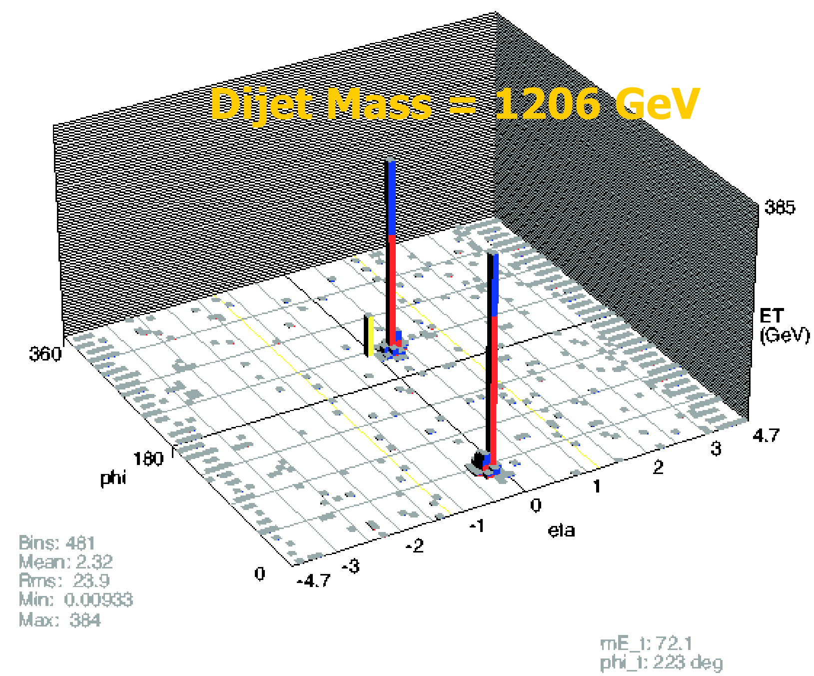

1222318 Run : 152507 EventType : DATA | Unpresc: 0,32,33,3,35,8,40,9,41,10,11,12,13,45,15,17,49,19,21,23,56,5
r-φ view

CDF

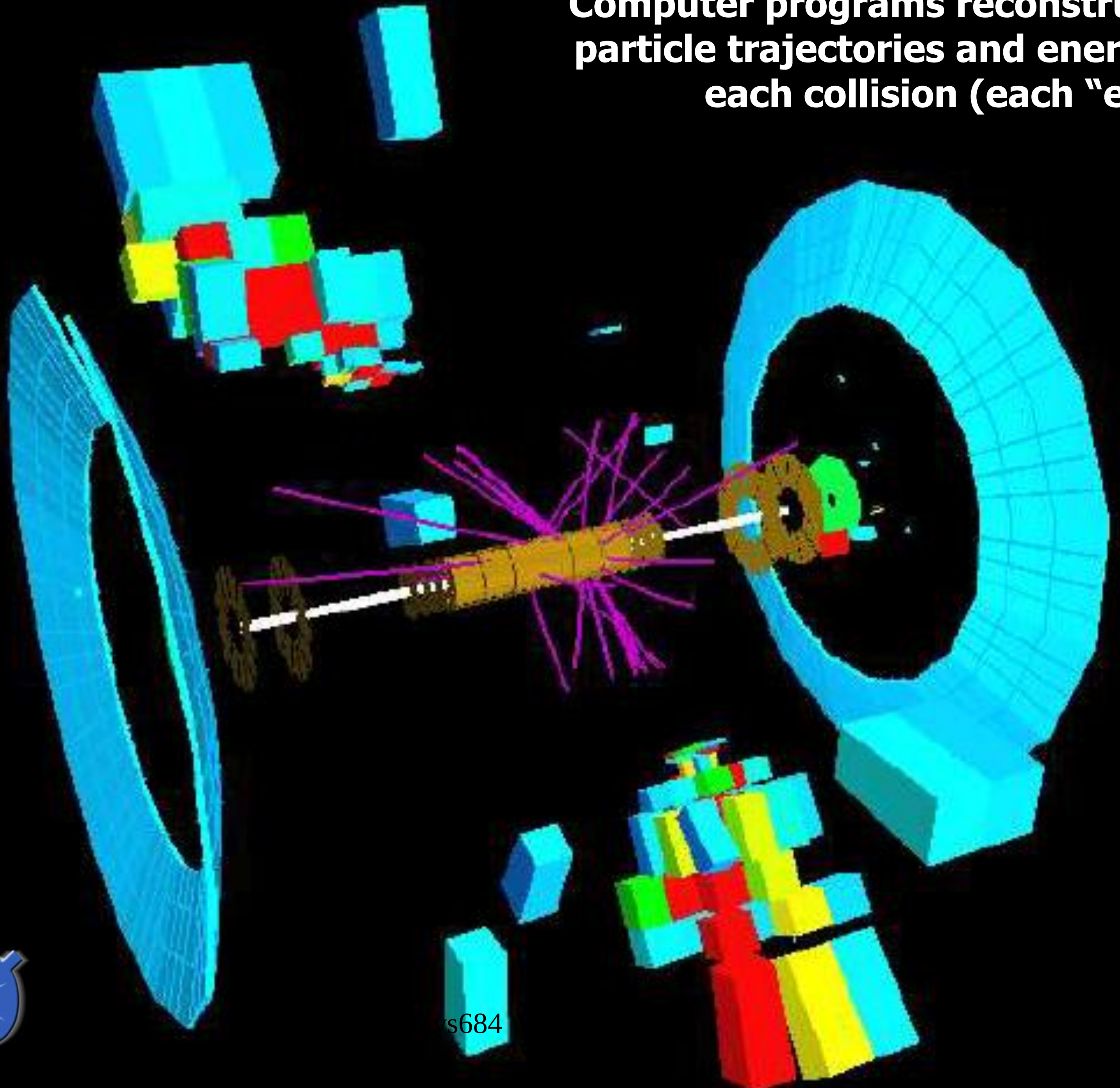

High mass di-jet event
(Mass = 1364 GeV/c2)
2
0
η


ET scale: 436 GeV
-3.7
3.7

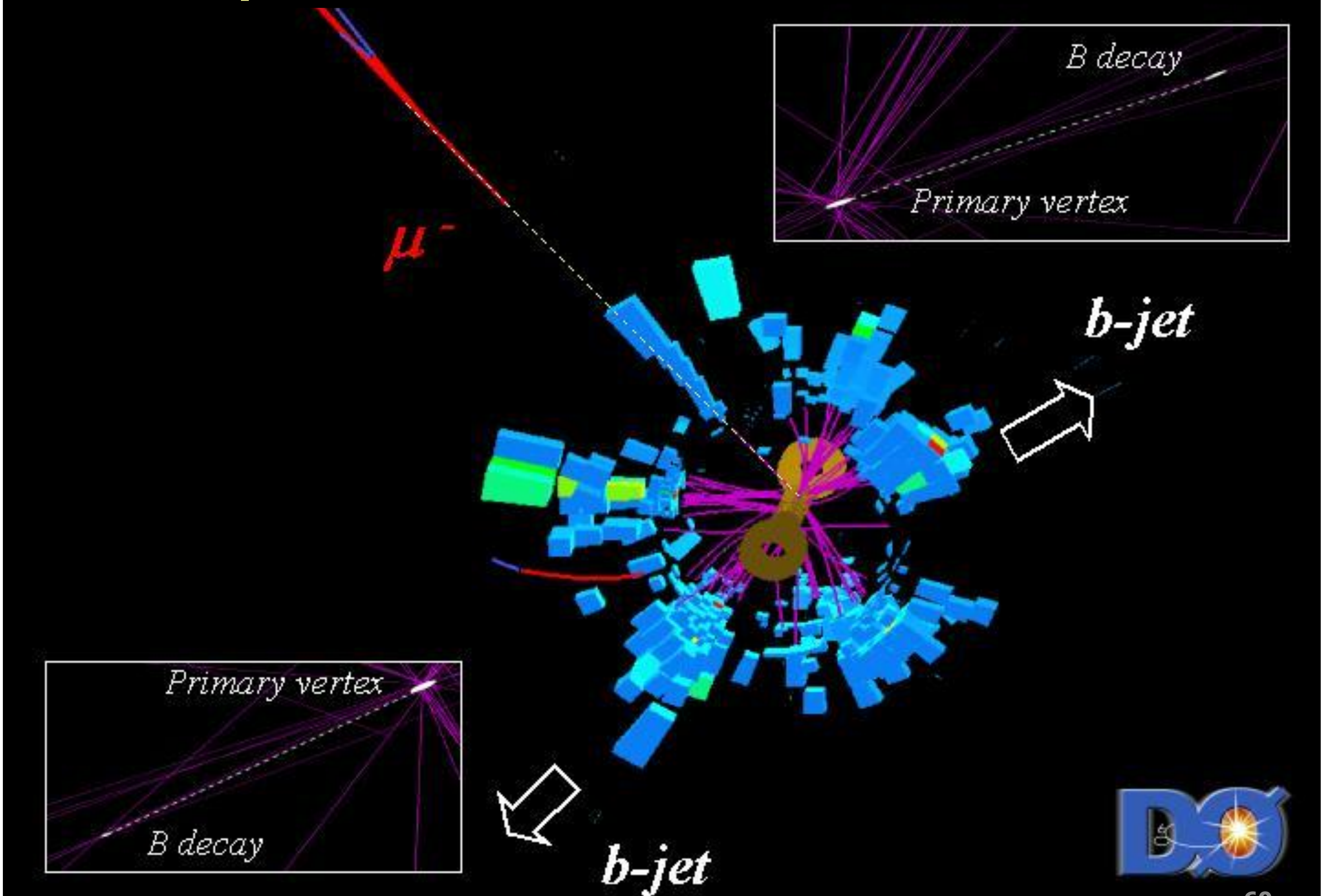
D0


Dijet Mass = 1206 GeV
385
ET (GeV)
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
Bins: 481
Mean: 2.32
Rms: 23.9
Min: 0.00933
Max: 384
mE_t: 72.1
phi_t: 223 deg

Computer programs reconstruct the particle trajectories and energies in each collision (each “event”)



Run II top candidate



Complicated Collisions

A simulated event in ATLAS (CMS) $H \to ZZ \to 4\mu$

pp collision at $\sqrt{s}$ = 14 TeV, $\sigma_{inel.} \approx 70$ mb

$\times 10^{-12}$

We are interested in processes with $\sigma \approx 10\text{–}100$ fb

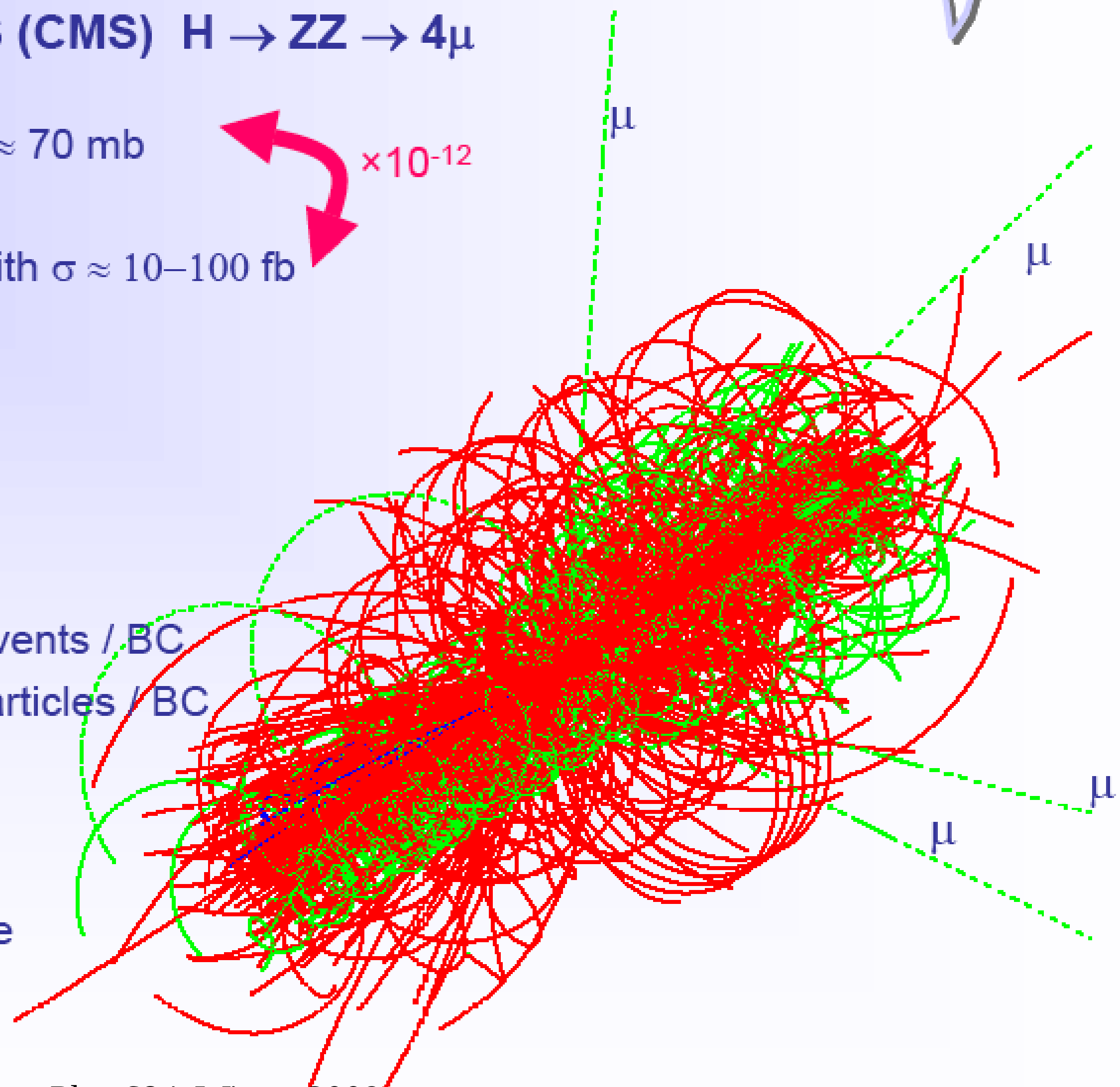
$L = 10^{34}$ cm^{-2} s^{-1},

bunch spacing 25 ns

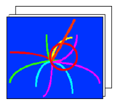
$\approx$ 23 overlapping minimum bias events / BC

$\approx$ 1900 charged + 1600 neutral particles / BC

Brave people have started to
think about a Super LHC upgrade
to $L = 10^{35}$ cm^{-2} s^{-1} !!!



Data Acquisition (CMS)



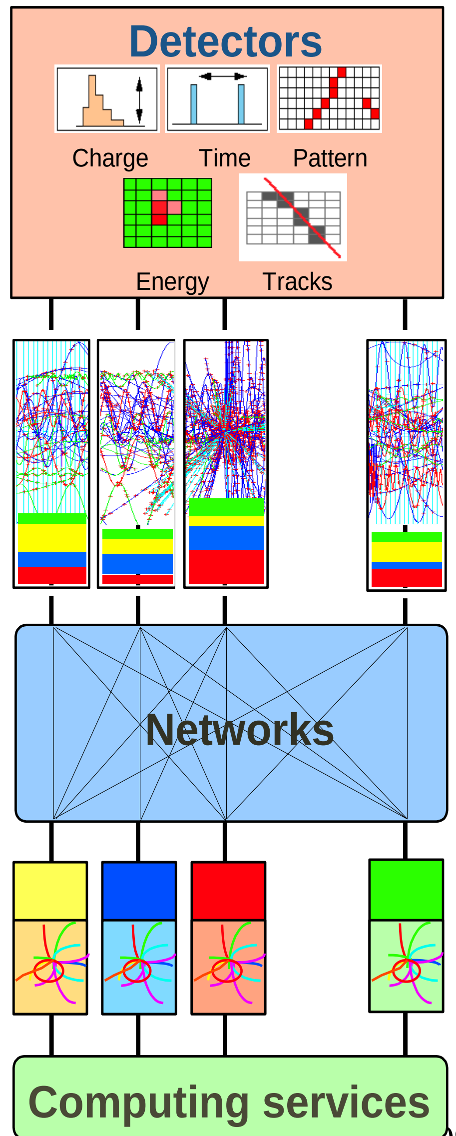
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

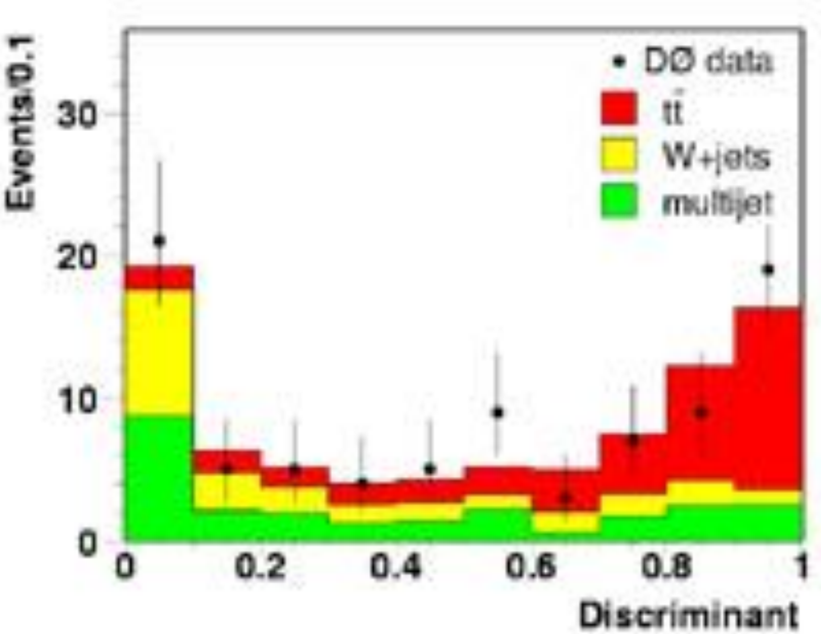
EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

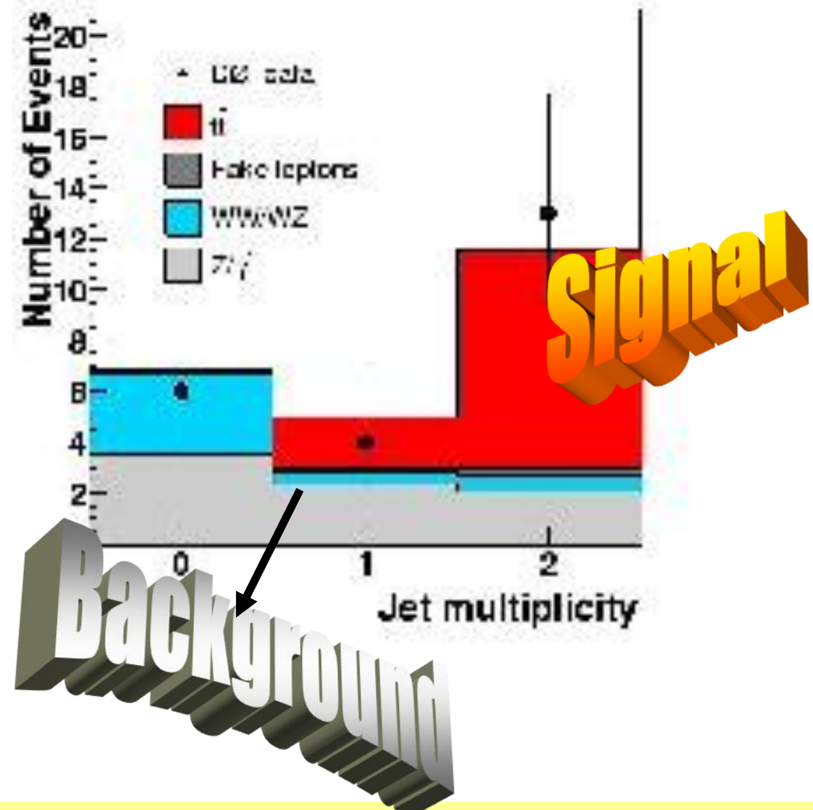
5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

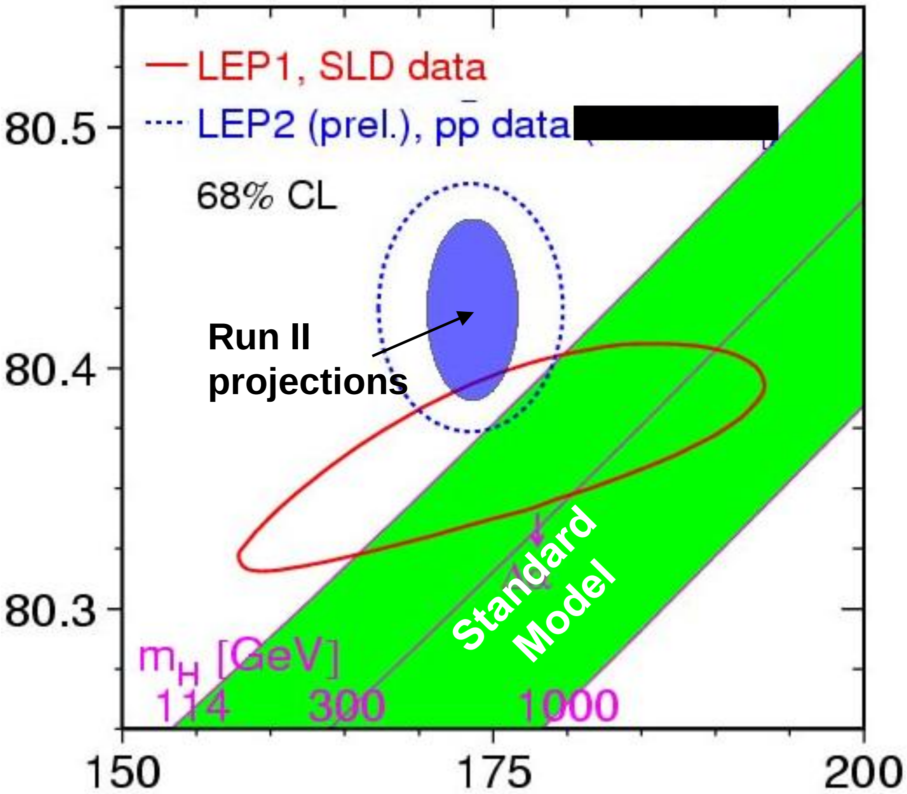
Finding the Signal

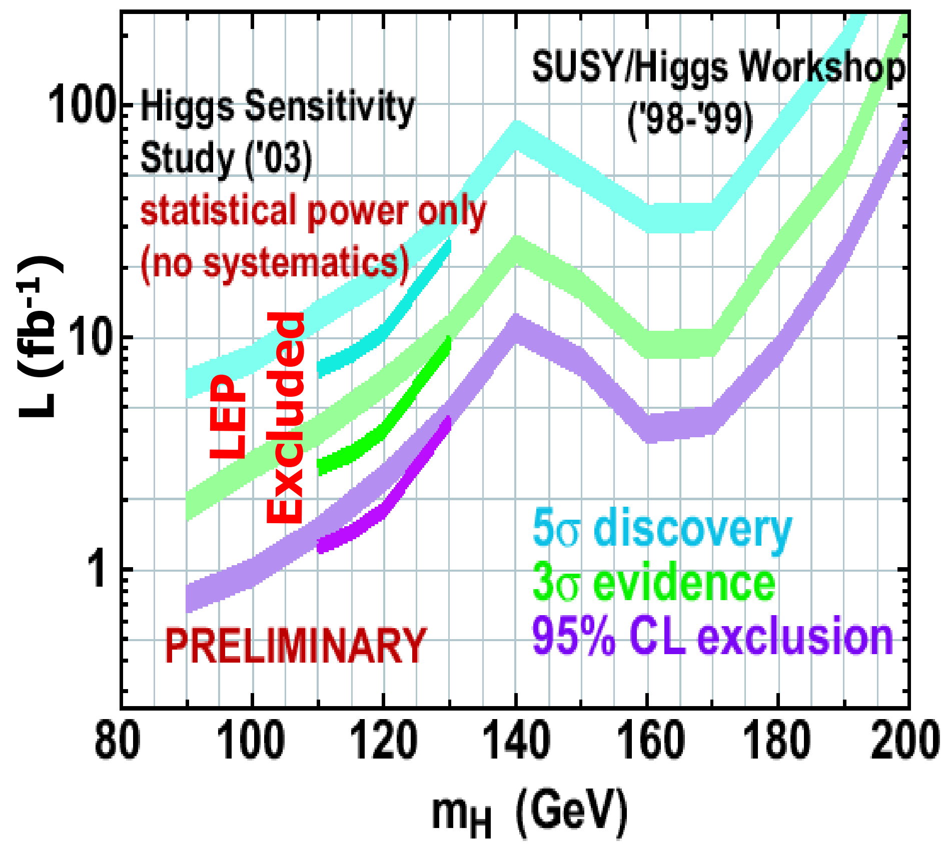




- Count the number of events seen in a particular channel ← N(data)
- Estimate the number of events from known, expected phenomena ← N(Bkg)
- Signal is the excess over the known, predicted background
- N(signal) = N(data) –N(Bkg)

The Higgs Boson





What do we seek?

Higgs, SUSY, dark matter, other exotics, surprises!

- Newton's unfinished business… what is mass?
- Our little embarrassment… what is 96% of the Universe made of?
- Nature's favouritism for matter over antimatter
- Are there new symmetries? New forces?
- Are the forces unified?
- …

There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy.

-- Shakespeare

Experiments may reveal something unexpected and exciting!

EXTRA SLIDES

Luminosity

- Collider Luminosity

Instantaneous Luminosity $L \approx \dfrac{\text{Rev. Freq.} \times Nbunches \times \text{Np} \times \text{N}\bar{\text{p}}}{\text{Trans. Beam Area}}$

Tevatron luminosity > 1x 10^{32} cm^{-2} sec^{-1}

Integrated Luminosity $= \int L dt$ **expressed as inverse picobarns or inverse femtobarns**

1 barn =10^{-24} cm^2 **measure of cross section**

Run 1 Int. Lum ~ 125 pb^{-1}
Run 2, already delivered ~1200 pb^{-1}

- Event Rate

$$N = L \times \sigma$$

Cross-section σ ← effective area of interaction, cm^2
← probability for a process to occur

Some Numbers…

- In the Tevatron we inject 36 bunches each of protons and antiprotons (pbars)
  - $N_{protons} = 2\times10^{11}$, $N_{pbars} = 4\times10^{10}$, in each bunch
  - *Revolution frequency* = (3×10^5 km/sec)/6 km,
  - *Transverse area of beams* $A = \pi\,(60\ \mu m)^2 = \pi\,(0.0060\ cm)^2$
  - *Luminosity = 36 . f. Nprotons. Npbars /A* → L = **1 x 10^{32} cm^{-2} sec^{-1}**
- Cross section of a proton/antiproton collision

  $$\sigma \sim 6 \times 10^{-26}\ cm^2$$
- Event rate = L. σ
- So, we get about 6×10^6 collisions per second!
  - The Collider detectors must be able to gather, examine, sort, store data at this rate
- Each proton/antiroton has energy of

  $$980\ GeV = 980 \times 10^9 \times (1.6 \times 10^{-19}\ J) = 1.6 \times 10^{-7}\ J$$
- So, *power* delivered in the collision region is only about

  $$2 \times 1.6 \times 10^{-7}\ J \times 6 \times 10^6\ /sec \sim 2\ watt!$$

Data Analysis

- How do we discriminate signal from background?
- How do we make precision measurements?

What are we up against?

Let us take top quark production to see how it all works

- 2.5 Million p-pbar crossings/sec most of which are "uninteresting"!
- Total inelastic cross section ~ 60 mb = 6x 10^{-2} barn
    - **1 barn =10^{-24} cm^2**
  - At $\mathcal{L}$ = 10^{32} cm^{-2} sec^{-1}, N = 6 Million interactions /sec
- Top-antitop pair production cross section $\sigma(t\bar{t})$ ~ 6.7 pb = 6.7 x 10^{-12} barn
  - 10 orders of magnitude lower!
  - 1 top pair event for every 10 billion "uninteresting" events!

→Finding a needle in a huge haystack!